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Asian pharmaceutical and medical device industry innovation - perspectives up to 2050

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Asian pharmaceutical and medical device industry innovation - perspectives up to 2050

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Fairness of the Distribution of Public Medical and Health Resources

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The fairness of health services is an important indicator of the World Health Organization's performance evaluation of health services, and the fairness of health resource allocation is the prerequisite for the fairness of health services. The research in this article aims to explore how to use health and medical resources fairly and effectively to allocate health resources in different fields, populations and projects, in order to achieve the maximization of social and economic benefits of health and medical resources. In the study of the distribution and equity of public health and medical resources, we comprehensively apply Gini coefficient, Theil index, Lorentz curve and difference index, based on the theory of health resource allocation and the theory of health equity, the province's health service resources have been researched and evaluated, combined with regional health planning theories and public health theories, a variety of scientific methods were used to analyze community health service resources at all levels across the country. At the same time, we reviewed the journal literature about the treatment of patients and children, and analyzed the patients admitted to medical institutions in various regions. The research in this paper found that from 2016 to 2020, the Gini coefficient of the province's health institutions according to population distribution has been fluctuating between 0.14 and 0.17. During this 5-year period, the Gini coefficient of the distribution of medical and health expenditures by population shows a downward trend year by year. From 2019, reach below 0.1, this shows that the fairness of the allocation of health resources according to population has a clear trend of improvement.

Keywords: public healthcare, health resources, health resource allocation, resource justice, physical health

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INTRODUCTION

Since the reform and opening up, our country's health care has developed rapidly, and the health of the people has been greatly improved. With China's accession to the WTO, the primary problem facing the Chinese government and the medical and health system is how to adapt to the rapid changes in domestic and foreign events and formulate a consistent health policy. The 17th National Congress of the Communist Party of China proposed to build a well-off society in an all-round way, and to create a new situation of socialism with Chinese characteristics as its work goal. At the same time, it calls on the medical and health industry to "create and improve the medical and health system and health level, and promote the physical and mental health of the people" as an important part of improving people's lives and promoting healthy development. In addition, the new round of medical reform proposes that medical and health services always maintain a public welfare nature. In order to achieve the goal of everyone enjoying basic medical and health services, this stipulates that the government's regulation of health resource management becomes the main choice, and the government's macro-control must be led to achieve fairness and effectiveness. At the same time, the people actively cooperate with the government's actions, raise problems and solve them with the joint efforts of the government and the people, so as to make the distribution of public health resources fair and stable.

Physical health is the basis for people to engage in other activities. Medical and health activities are social activities that maintain and restore people's basic survival and activity skills. The prerequisite for the smooth progress of medical and health activities is the reasonable management of medical resources and health resources, and reasonable enjoyment of medical and health resources is the fundamental guarantee for safeguarding the interests of human health. It is a key content related to the overall development of the health industry and a necessary condition for the stable, coordinated and healthy development of the pharmaceutical and health industry. How to manage health resources scientifically and rationally, make full use of limited resources, better serve the people, and improve people's physical and mental health has become an urgent problem to be solved.

Combined with the research progress at home and abroad, different scholars have different views and explorations on such issues. Sam and Nunn criticized the current knowledge about patient and public participation, here called patient and public participation (PPI), and called for the development of robust and theoretically based strategies throughout the continuity of medical education. The study draws on a series of relevant literature and regards PPI as a response process related to the patient-centered learning agenda (1). Cheng et al. proposed an attention-based two-way gated recurrent unit (AB-GRU) medical migration prediction model to predict which hospitals patients will go to in the future (2). The focus of Embrett and Randall's research is to understand how the framework of the problem affects government decisions related to the cancellation of medical service funding. To achieve this goal, a framework describing how the problem frame or explanatory narrative affects government policy decisions was developed and applied to actual cases (3). Osadchuk et al. research aims to ensure the protection and enhancement of everyone's physical and mental health by providing high-quality medical and preventive care, and to maintain their long-term active life. Although human health does not have an accurate market price, it has the highest value for society and individuals (4). Mohammad et al. study investigated the prevalence and related risk factors of job burnout among public service medical staff in Kota Kinabalu, Sabah who participated in the fight against the Covid-19 epidemic. A cross-sectional study was conducted involving 201 medical personnel working in all government hospitals and health clinics (5). Ruiz-Mejía and Méndez-Durán studied the reasons for the high incidence of chronic non-communicable diseases such as diabetes, systemic hypertension, overweight, obesity, dyslipidemia and metabolic syndrome (6). Feng and Pan's research on telemedicine allows limited available medical resources to be shared and fully utilized, and many economically underdeveloped provinces can enjoy higher-level medical sharing services. The overall design of the public health emergency management system will be based on the Internet of Things in accordance with system functions and low latency (7). In order to capture the impact of the spatial heterogeneity of the resources available in the environment and the public health system on the persistence and extinction of infectious diseases, Jlng GE proposed a simplified spatial SIS reaction diffusion model. This model has the allocation and utilization efficiency of medical resources (8). Although these studies give the impact of medical services on expenditures, they are only one-sided and do not analyze the fairness of the allocation of public medical and health resources in terms of population distribution and geographic location.

The innovations of this article are embodied in several aspects: first, it essentially explains the importance of fair distribution of public resources, and puts forward the principles and standards of fair distribution. Second, analyze whether residents have equal access to public resources from the perspective of knowledge and geographical differences. Third, in terms of analysis methods, the method of combining statistics and qualitative analysis is used to analyze the effectiveness of health resource allocation and public health benefits. At the same time, through field research and empirical analysis, the factors that affect the effective allocation of public health resources are explored.

METHODS ON THE FAIRNESS OF THE DISTRIBUTION OF PUBLIC MEDICAL AND HEALTH RESOURCES

Allocation of Health Resources

Health resource allocation refers to the distribution and transfer (flow) of health resources to health departments and health care providers. It is the government or the market that enables health resources to be appropriately allocated to different types, different departments, different institutions, different projects, and different groups of people, thereby increasing the benefits of the community and the value of health resources.

It can be seen from **Figure 1** that all social resources are inseparable from health and medical resources. At the same time, in **Figure 2** we can also see that health care is closely related to our lives. The development of health services has become an important indicator to measure the comprehensive strength of a country and region. How health resources are allocated determines whether health output can meet the goals of comprehensive social and economic development with high quality and quantity. This is related to the basic living issues of hundreds of millions of people. It is related to the development level of the whole country's health service (9). Today's medical and health services have undergone major changes compared with those before the reform and opening up. Today's medical and health services can guarantee people's basic living needs and can make people sick and treatable. Before the reform and opening up, our country realized the allocation of health resources through a planning mechanism. The main problem with this allocation model is that it cannot meet the requirements of multi-level growth and large-scale production of medical care in rural and urban communities. Under the condition of

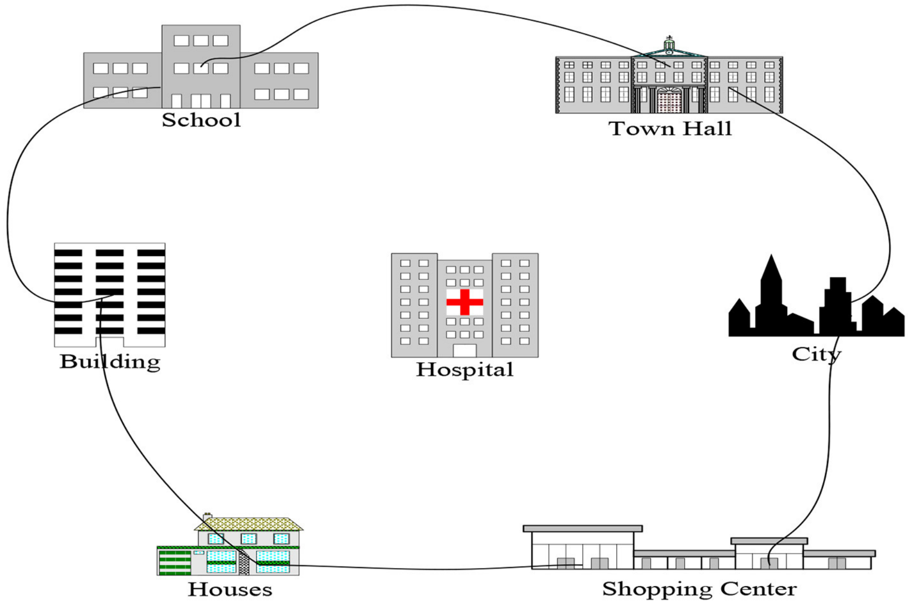

FIGURE 1 | Allocation of health resources.

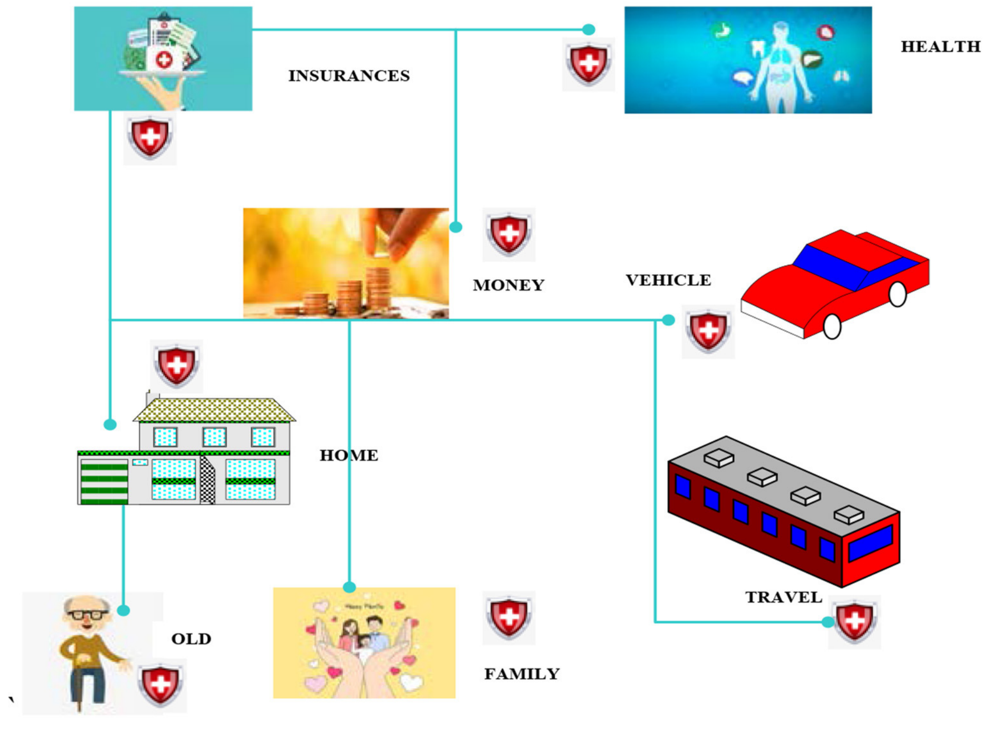

FIGURE 2 | Health care and life.

limited government finances, the overall allocation of health resources is insufficient and the allocation efficiency is relatively low; with the transition of the financial system from a planned econoour to a market econoour, the government's control over medical institutions has gradually loosened, and the national medical reform has also moved toward a market-oriented path, advocating market-oriented configuration and operation. The proportion of government investment in the medical and health field has fallen, and medical expenses have risen rapidly. Under this model, although it is possible to rapidly increase health resources and improve allocation efficiency to a certain extent, due to the profit-seeking characteristics of the market, the end result is that health resources flow to areas with more developed economic development and strong ability to pay, while ignoring the fairness of health resource allocation, leading to the lack of public welfare in public hospitals. There has been a serious problem of "difficult and expensive medical treatment," which eventually led to a decline in the efficiency of medical and health services, which obviously deviated from the Pareto efficiency curve. Therefore, excessive commercialization has not only brought social injustice, but also caused the loss of profitability (10). Therefore, in order to ensure fairness, the government must actively and reasonably participate in the allocation of health resources, and at the same time, it should give full play to the role of the market mechanism, improve the efficiency of health resource allocation. It is hoped that in the future, the fairness of the distribution of public medical and health resources will be realized, the problems of "difficult and expensive medical treatment" will no longer arise, and the allocation of health resources will eventually be shared by all.

Principles of Health Resource Allocation

Principles Based on Health Needs and Medical and Health Service Needs

The objects of medical and health services and the end of the service process are people in society. Therefore, the allocation of medical and health resources should reflect the people-oriented concept, focusing on ensuring the health of the whole people, and improving people's health and quality of life. The needs of society determine the provision of medical and health services, and the allocation of medical and health resources should be oriented to meet social needs. Coordinating and rationally distributing limited medical resources and health resources through medical and health service design, and effectively balancing regional surplus or shortage of medical and health resources through resource allocation and redistribution (11).

The Principle of Adapting to Economic and Social Development

Reform and opening up and economic globalization have promoted social and economic development, and extensive social changes have also followed. The improvement of people's living standards and the increase in health awareness put higher demands on our country's medical and health services. It is bound to affect and change the allocation of medical and health resources in terms of total, quality, and structure (12). The increasing purchasing power and demand of residents for medical and health services makes the provision of medical and health services not only characterized by sufficiency and diversity, but also taking into account the important factors of the quality, balance and sustainability of medical and health services, to adapt to economic and social development.

The Principle of Fairness and Efficiency

Fairness and effectiveness is an important principle for the government to allocate medical and health resources, and it is also a long-term goal (13). Equity in the field of health services refers to ensuring that every member of society has an equal opportunity to enjoy medical and health services based on the allocation of medical and health resources on demand. Medical and health efficiency includes two concepts of econoour and ethics, that is, unreasonable allocation of health resources is both a waste and immoral (14). Paying attention to justice and fairness can not only promote the realization of fairness and fairness and the improvement of human health, but also an important guarantee for health and sustainability, and the sustainable development of health services.

Ensure the Principle of Focusing on the Overall Situation

The requirement of "prevention first, grassroots as the focus, and equal emphasis on Chinese and Western medicine" is a policy guideline for improving the status quo of medical and health care. Due to the relatively slow development of the rural econoour and poor basic medical and health conditions, the current situation of rural medical and health is far from that of cities. The degree of improvement in rural medical and health conditions is related to the reform process and development trend of our country's overall medical and health services (15). The allocation of medical and health resources must start from the grassroots level, focusing on improving the level of rural medical and health care. Medical and health investment and related policies need to focus on rural areas and strive to narrow the gap between urban and rural areas. Implement basic medical and health services in rural areas, and ensure that farmers enjoy fair and effective rights to basic medical and health care. Effectively solve the major medical and health problems in rural areas such as difficulty in seeing a doctor, expensive medical care, poverty due to illness, and illness due to poverty, etc., it is necessary not only to improve the health of rural residents, but also to achieve social fairness and justice in the process of medical and health resource allocation (16).

Commonly Used Methods of Research on Equity of Health Resource Allocation

Gini Coefficient

The Gini Coefficient (Gini) is a widely used analysis indicator to measure the income gap of residents in a country (or region). Calculate the Gini coefficient according to the Lorentz curve and the type of Gini coefficient. Quantitative indicators are obtained through data processing and figure area estimation, and the degree of difference in the allocation of medical and health resources is analyzed (17). When the Gini coefficient is lower than 0.2, it means that the allocation of medical and health resources is absolutely even; 0.2 to 0.3 means that the configuration is relatively average, and there is a small gap;0.3 to 0.4 means that the configuration is relatively average and reasonable, but there is a certain gap; 0.4 to 0.5 means that the configuration gap is large. Above 0.6 indicates a huge gap in allocation, and 0.4 is used as a warning line for the gap in resource allocation. As follows:

$$G = \sum_{i=1}^{n} A_i B_i + 2 \sum_{i=1}^{n-1} A_i (1 - C_i) - 1 \quad (1)$$

Among them, A_i is the ratio of the population (or geographic area) of each region to the total population (or total geographic area); B_i is the ratio of the number of health resource indicators in each region to the total number of corresponding health resource indicators; $C_i = B_1 + B_1 + ...B_i$ is the cumulative percentage of health resources. The Gini coefficient is between 0 and 1. The closer the Gini coefficient is to 0, the fairer the distribution of medical and health resources; the closer the Gini coefficient is to 1, the more unfair the medical and health resources are (18).

Theil Index

The Theil index is an important indicator to measure the balance of social resource distribution in a region. In Western science, the Theil index is a method of measuring balance. It checks the fairness and inequality of the distribution of resources by checking whether the weight of the population corresponds to the weight of its income (19). The Theil index value is >0, and its value is smaller, which indicates that health resources can be allocated in this field more effectively. The calculation formula of Theil index is as follows:

$$T = \sum_{i=1}^{n} A_i \log\left(\frac{A_i}{B_i}\right) \quad (2)$$

In the formula, if A_i is the proportion of each city's population in the province's total population; then B_i is the proportion of each city's health resources in the province's total health resources.

Decomposition of Theil index:

$$T_{\text{total}} = T_{\text{between groups}} + T_s \quad (3)$$

$$T_s = \sum_{j=1}^{w} A_j T_j \quad (4)$$

$$T_{\text{Between groups}} = \sum_{j=1}^{m} A_{\text{j}} \log \frac{A_j}{B_j} \quad (5)$$

In the formula, T is always the overall difference; within the T group is the difference in the allocation of health resources in Type I, Type II, and Type III areas. Among the T groups are the differences in the allocation of health resources among the Type I, Type II, and Type III areas. A_j is the ratio of the population of each region to the total population. B_j is the ratio of the amount of health resources in each region to the total amount of health resources. T_j is the Theil index of each region. Contribution rate of differences within and between groups to the total Theil index: contribution rate of difference within groups = within T group/T total; contribution rate of difference between groups = T between groups/T total.

Lorentz Curve

American economic statistician M. Lorenz first proposed the Lorenz curve to study the optimal allocation of urban and rural medical and health resources, and to study the rational distribution of property, land and income (20).

Suppose the distribution density function of the income variable a is *s(a)* (that is, the percentage of the population with income a to the total population), the total population is M, then the population whose income is $<g$ is $\int_0^g Ms(a)da$. Its percentage of the total population is:

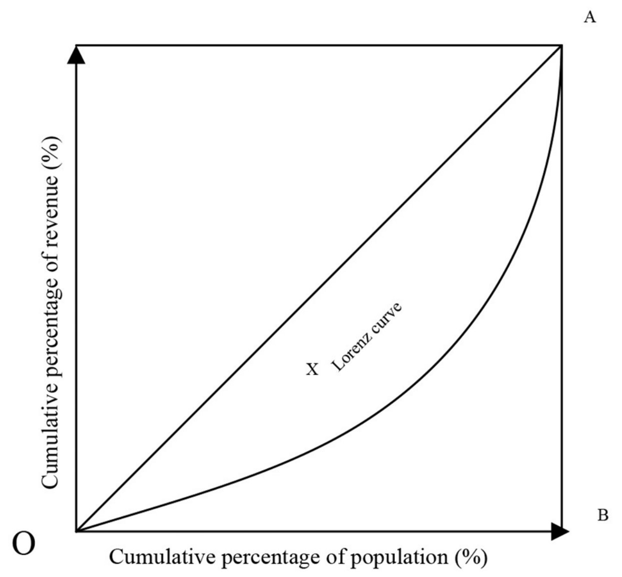

FIGURE 3 | Lorentz curve.

$$S(g) = \int_0^g Ms(a)da/M = \int_0^g s(a)da \quad (6)$$

The sum of the income of all people whose income is $<t$ (called cumulative income) is $\int_0^g aMs(a)da$. Its proportion in total income is:

$$H(g) = \int_0^g aMs(a)da/\int_0^\infty aMs(a)da = 1/a \int_0^g as(a)da \quad (7)$$

Among them is the expected value of income $a = \int_0^\infty as(a)da$ or the total average income of the society. By the parametric equation:

$$S = S(g) = \int_0^g S(a)da (g \geq 0) \quad (8)$$

$$H = H(g) = 1/a \int_0^g as(a)da \ (g \geq 0) \quad (9)$$

Figure 3 the horizontal axis of the Lorenz curve is the cumulative percentage of the population, and the vertical axis is the corresponding cumulative percentage of medical resources. If the curve coincides with the diagonal, it indicates that the health resources are at an absolute average level. If the curve is close to the diagonal, it means that social health resources are loosely distributed and low-income groups appear; if the curve is close to the diagonal, it means that it is below the diagonal and inclined to the horizontal axis. It can be seen that the fairness of social health resources is returning, mainly in high-income groups.

The Lorentz curve has the following properties:

(1) S(0) = 0, H(0) = 0, that is, 0% of the population's income accounts for 0% of the total income; and $S(\infty) = 1$, $H(\infty) = 1$, that is, 100% of the population revenue accounts for 100% of total revenue.

(2) The Lorentz curve is increasing because:

$$dH/dS = dH/dS \div dS/dg = gs(g)/as(g) = g/a \geq 0 \quad (10)$$

(3) The Lorentz curve is convex downward because:

$$\begin{aligned} D^2H/dS^2 &= d(dH/dS)\ /dS \\ &= d(g/a)\ /dg \div dS/dg = 1/as(g) \geq 0 \end{aligned} \quad (11)$$

Dissimilarity Index

The dissimilarity index (ID) is to use the health proportion of a certain class and the relative population proportion of this class to analyze the concentration of health in a certain class or evenly distribute in each class, and evaluate the degree of health difference of each class (21, 22). If there are $N = 1, 2, 3,..,$ n social classes, the dissimilarity index is:

$$ID = \frac{1}{2}\sum_{n=1}^{i}\left|T_{nx} - T_{ny}\right| \quad (12)$$

Among them, Tnx is the proportion of the population in the Nth class, and Tny is the proportion of the population in the Nth class. The greater the difference between the two, it shows that the higher the degree of unfairness in the health of this class. The ID value is between 0 and 1. The smaller the ID value, the more uniform the health distribution, and the larger the ID value, the more uneven the health distribution.

Concentration Index Method

The concentration index method (CI) is a more appropriate method to measure the degree of health inequality related to socio-economic conditions. This is an index recommended by the World Bank to assess the inequality of health services under different socio-economic conditions (23, 24). The concentration index is sorted according to the per capita net income level, so that the research variable is related to the personal economic income, which can well-reflect the impact of the economic level on the equity of the allocation of health resources. It is a method to assess the degree of per capita health inequality and measure the degree of health inequality related to socio-economic conditions (25).

The calculation formula of the concentration index is:

$$M = \frac{1}{2}\sum_{i=0}^{n-1}(A_i + B_{i+1})(A_{i+1} - A_i) \quad (13)$$

$$A_0 = 0, B_0 = 0 \quad (14)$$

$$CI = 2 \times (0.5 - S) \quad (15)$$

In the formula, the value of A is arranged according to the annual per capita disposable income of each resident from small to large, and then the cumulative percentage of the population in each region is calculated; B value is the cumulative percentage of community health service resource allocation; i is the ranking of each region in descending order of economic level, and n is the number of regions. The value range of the concentration index CI is [−1, 1], when its value is 0, it means fairness or equality, when its value is positive, it means that the allocation of health resources is concentrated in higher-income groups, and there is inequality in favor of the rich; when its value is negative, it means that the allocation of health resources is concentrated in lower-income groups, and there is inequality in favor of the poor.

DEA Measurement Algorithm

The DEA calculation method is used to measure the efficiency of medical and health resources in various provinces. Under the established conditions, the investment of financial resources has achieved the maximum output of medical and health services, then the efficiency of the medical and health expenditure of the place is effective. That is, it is efficient to transform financial resource input into medical and health service output. The calculation method can be expressed by the following linear programming equation:

$$Maximize\ \frac{\sum_{a=1}^{k} m_a t_{ao}}{\sum_{b=1}^{w} h_b k_{bo}} = \theta \quad (16)$$

$$Subject\ to\ \frac{\sum_{a=1}^{k} m_a t_{aj}}{\sum_{b=1}^{w} h_b k_{bj}} \leq 1(j = 1, 2 \cdots n\ m_a \geq 0, h_b \geq 0) \quad (17)$$

Evaluation Method of Resource Utilization Efficiency

The rank sum ratio method (RSR) is a non-parametric evaluation method proposed by Chinese statistician Tian Fengtiao. It has the advantages of overcoming the shortcomings of individual indicator analysis and reflecting the comprehensive level of multiple evaluation indicators, and is widely used in the field of health management. Formula for calculating rank:

$$RSR = \sum\nolimits_{a}^{R} a \times b \quad (18)$$

In the formula, a is the number of indicators, and b is the number of groups.

Calculate the Weighted Rank Sum Ratio (WRSR) of Medical and Health Resource Allocation

The weighted WRSR value calculation formula can calculate the weighted rank sum ratio of medical and health resource allocation:

$$WRSR = \frac{1}{k}\sum_{b=1}^{a} X_b Y_{cb} \quad (19)$$

where k is the sample content, and a is the number of evaluation indicators. Using the probability unit PRobit as the independent variable and WRSR as the dependent variable, calculate the linear regression equation, namely:

$$WRSR = -0.8546 + 0.2699PRobit \tag{20}$$

EXPERIMENT ON THE FAIRNESS OF PUBLIC MEDICAL AND HEALTH RESOURCE DISTRIBUTION

There are many methods to study the fairness of community health service resource allocation, but any method has certain limitations or deviations and cannot fully reflect the fairness of community health service resource allocation. The main reason for the deviations in the reform of the medical and health system is that some regions push all local public hospitals to the market indiscriminately, and some places propose to transplant the property rights reform of industrial and commercial enterprises and sell public hospitals; In addition, some hospitals that are obviously public welfare have also adopted certain market-oriented practices, which aroused people's discussion and dissatisfaction. Therefore, the basic starting point of this study is to use multiple methods to evaluate the fairness of community health service resource allocation from different angles. At present, the academic circles generally use Gini coefficient and Theil index as the main indicators to evaluate the equity of health service resource allocation. Although the use is simple and the effect is intuitive, it is not comprehensive, and may cover up some internal unfairness. For example, the Gini coefficient is low, and it seems fair on the surface, but there may be a certain group that over-occupys community health service resources, and there is inequality that is beneficial to this group. Therefore, this study uses Gini coefficient, Theil index and concentration index to make up for the flaws in the research method of the equity of community health service resource allocation.

Research on the fair distribution of public health resources makes full use of the Gini coefficient, Theil index, Lorentz curve and difference index, based on the theory of health resource allocation and the theory of health equity, the urban resources of community health services are evaluated, and a variety of methods are used to analyze the fair distribution of urban health service resources. **Figure 4** is a research framework for the equity of the allocation of urban community health service resources.

After long-term construction and development, the province's medical and health services have continued to grow, and the basic urban and rural medical safety system has basically taken shape, formed a medical and health service system of a certain scale covering urban and rural areas, consisting of hospitals, public health institutions, and primary medical and health institutions. At the end of 2019, medical and health institutions developed moderately. In terms of quantity, there will be 7,003 health institutions of various types in the province in 2020, an increase of 0.89% over 2016; among them, there are 232 hospitals in the province, an increase of 3.4% over 2016; the total number of primary medical and health institutions is 6,037, an increase of 8.67% over 2016; 213 professional public health institutions, an increase of 32.67% over 2016; there were 10 other health institutions, a decrease of 35.71% from 2016.

It can be seen from **Figure 5** that from 2016 to 2020, the number of hospitals has not changed much, and the annual increase or decrease varies between 2 and 3; since 2016, the number of health centers and community service organizations has been on the rise, which is in line with the country's emphasis on improving the three-level medical and health network. Give full play to the leading role of serving prefecture-level hospitals and the backbone role of municipal health centers; from 2016 to 2019, the number of clinics fluctuates slightly, but the overall development is stable, but there has been a large decline in 2020, a decrease of 11.23%; the village clinic has been growing steadily since 2016, but it has declined in 2019, and then saw a substantial increase in 2020, an increase of 12.67% over the previous year.

At the same time, the distribution of patients admitted to medical institutions in the region was analyzed. In 2016, the total number of patients receiving treatment was 614,000, and the number of patients treated by health care institutions accounted for 90.2%. The number of diagnosis and treatment in 9 township hospitals accounted for 20.1% of the total number of hospitals under the bureau. As shown in **Figure 6**.

According to the above data analysis, more people will choose non-profit medical institutions organized by the government, and concentrated in urban hospitals. This is mainly due to economic development, the improvement of people's living standards and scientific lifestyles, the gradual enhancement of human health concepts, and the increasing demand for medical and health services.

EXPERIMENTAL DATA ON THE FAIRNESS OF PUBLIC MEDICAL AND HEALTH RESOURCE ALLOCATION

Equity Analysis of Health Resource Allocation Based on Gini Coefficient and Lorentz Curve

The province's health resources are divided into three aspects: human resources, material resources and financial resources. Human resource allocation data includes the number of health technicians, practicing (assistant) doctors and registered nurses; the material resource allocation data includes the number of health institutions and the number of beds; the financial resources data are mainly medical and health expenditures. Next, calculate the Gini coefficient of each health resource according to the population distribution, and calculate the Gini coefficient of each year according to the geographical area of the province. **Figures 7**, **8** respectively show the Gini coefficients of various health resources in the province from 2016 to 2020 according to population and geographical distribution. The population distribution is divided according to the number of people in each region, and the geographical distribution is divided

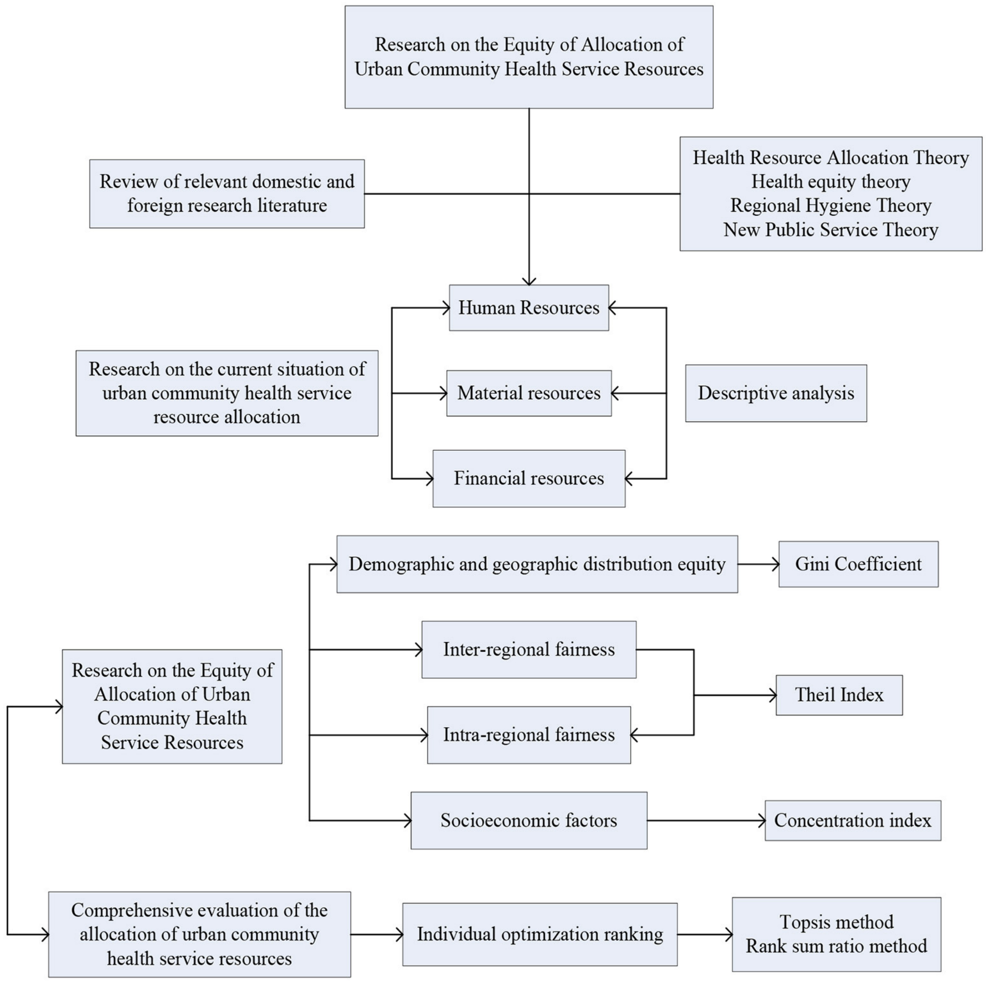

FIGURE 4 | The research framework of the equity of the allocation of urban community health service resources.

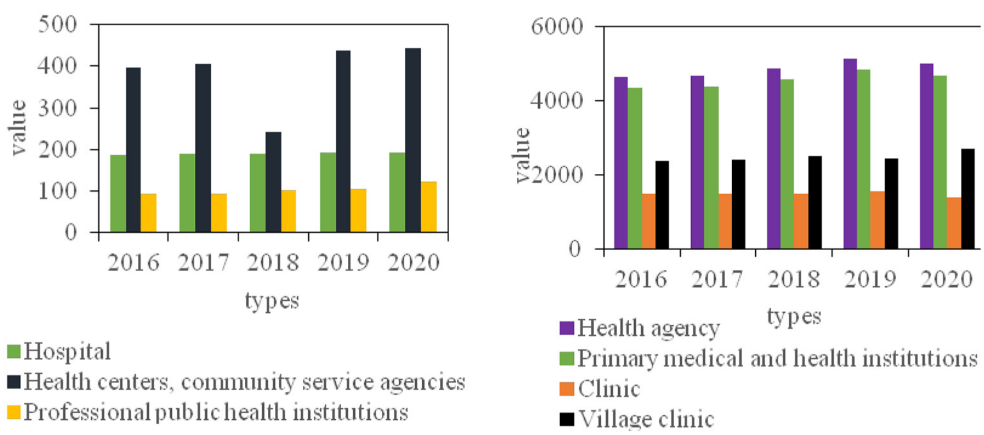

FIGURE 5 | 2016-2020 the development trend of medical and health institutions.

according to the different development conditions of each city, which can fully demonstrate whether its resource allocation is fair.

At the same time, in order to analyze the fairness of health resources in our province more intuitively, the Lorentz curve is drawn according to the difference of population distribution and geographical location, as shown in **Figure 9**.

From the perspective of the fairness ranking of various indicators of health resource allocation, regardless of whether it is configured by population or by region, the Gini coefficient of the allocation of health institutions is lower than that of other resource allocations, and its fairness is the best, followed by the distribution of medical and health expenditures. Registered nurses are the least fair indicator of the distribution of health resources. As shown in **Table 1**. The main reason for the poor fairness of resource allocation for registered nurses is that there are fewer staff engaged in the profession of nurses, which leads to the uneven distribution of nurses.

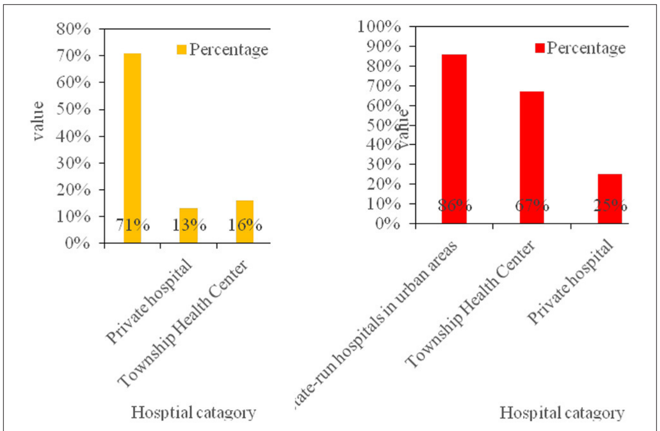

FIGURE 6 | The structure of the number of visits in 2016 and the comparison of the utilization rate of different types of hospitals.

From the above data, it can be concluded that from the perspective of population allocation, from 2016 to 2020, the Gini coefficients of the four indicators of health institutions, health technicians, practicing (assistant) physicians, beds, and medical and health expenditures all fluctuate between 0.07 and 0.30. It shows that these 4 health resources are in the best and fair state according to population allocation. The Gini coefficient of registered nurses is between 0.2 and 0.4, which is fairly fair. From the perspective of geographical distribution, the Gini coefficient of the two indicators of health institutions and medical and health expenditure is between 0.2 and 0.4, which is fairly fair. However, the Gini coefficient of health technicians, practicing (assistant) doctors, registered nurses, and geographically distributed hospital beds exceeds 0.4, and their fairness is in a warning state. The results show that the Gini coefficient of medical and health resources distributed by population is lower than that by geographical distribution, indicating that the fairness of medical and health resources distributed by population is better than that by geographical distribution. From 2016 to 2018, the Gini coefficient of beds, health technicians, doctors and nurses divided by population distribution in the province has not changed much, but by 2019, the Gini coefficient has dropped significantly; from 2016 to 2020, the Gini coefficient calculated by the population distribution of health institutions fluctuated between 0.14 and 0.17, with little change; in the past 5 years, the Gini coefficient of medical and health expenditure by population distribution has shown a downward trend year by year. Since 2019, it will fall below 0.1, but the Gini coefficient of the province's health resources divided by geographical distribution has not changed much. However, the Gini coefficient of various indicators divided by geographical distribution will increase slightly in 2020. This shows that the fairness of distribution of health resources according to

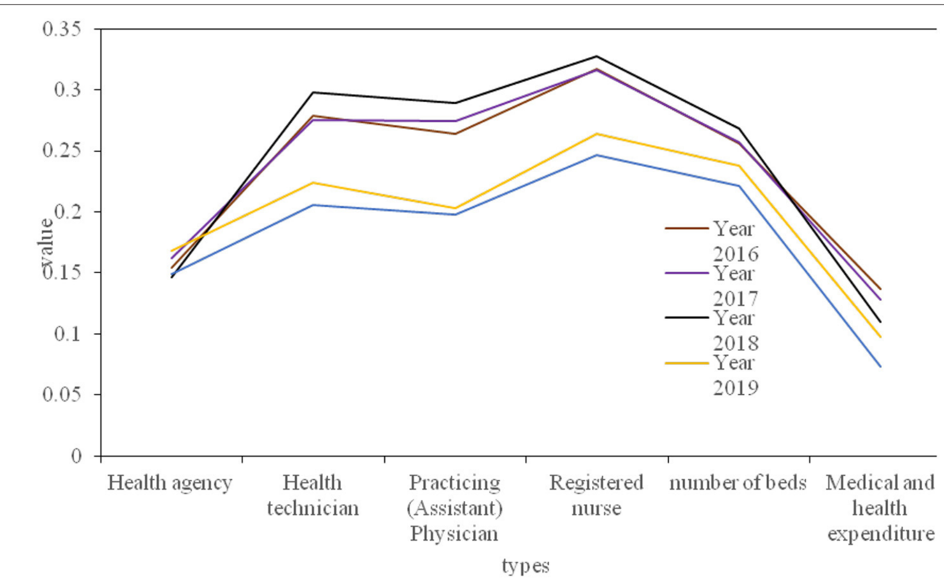

FIGURE 7 | 2016–2020 Gini coefficient of the distribution of various health resources by population.

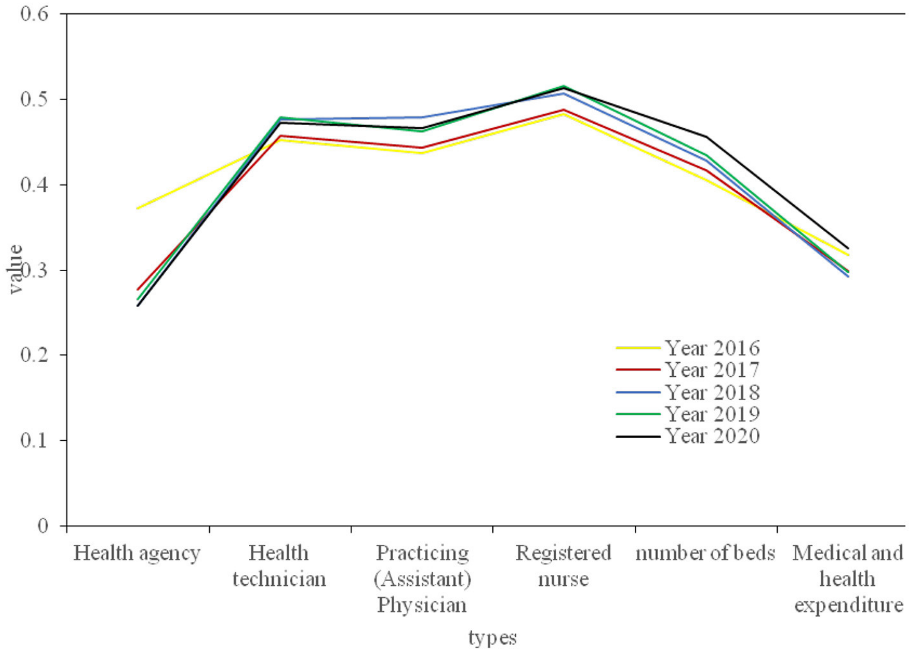

FIGURE 8 | 2016–2020 Gini coefficients of various health resources by geographic distribution.

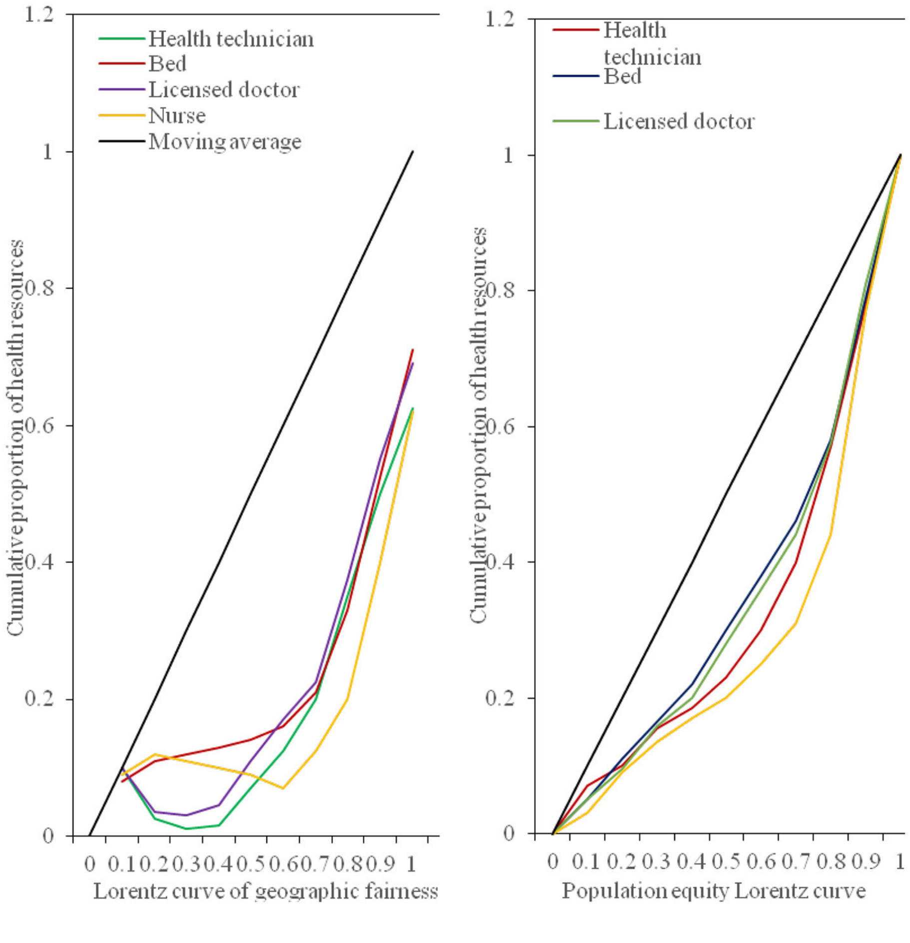

FIGURE 9 | The Lorentz curve of the geographic equity of the medical and health resources population.

population distribution has a significant improvement trend, but the fairness of distribution of health resources according to geographical distribution has declined.

Theil Index Evaluates the Balance of Health Resource Allocation in the Province

We make statistics on the allocation of bed resources in medical and health institutions in this province. According to the per capita GDP from 2015 to 2020, the province's cluster analysis is divided into 4 categories: Class I areas (economically developed areas), Class II areas (medium economically developed areas), Class III areas (economically underdeveloped areas). **Tables 2**, **3** respectively represent the Theil index of the province and each region, and the Theil index of the province's bed resource allocation and its decomposition.

From the above-stated Theil index, it can be concluded that the total Theil index for the allocation of bed resources in medical and health institutions in the province in 2020 is 0.086. The Theil index for Type I areas is 0.042, Type II areas are 0.002, and Type III areas are 0.022. On the whole, the number of II has dropped, from 0.125 to 0.086. Among them, the Theil index of Type I and Type II areas declined, and the Theil Index of Type III areas increased. Regarding the changes in the Theil index between regions and within the region, from 2015 to 2020, the Theil index for the allocation of bed resources in this province will drop from 0.101 to 0.081. Among them, the inter-regional Theil index decreased from 0.024 to 0.022, and the contribution rate of inter-regional differences increased from 23.66% to 27.64%. The regional Theil index dropped from 0.077 to 0.059, and the contribution rate of regional differences dropped from 76.34 to 72.36%. The population fairness of bed resource allocation in this province is better than geographical fairness. Geographic fairness has long exceeded the unfair warning line. The fairness of population allocation by professional public health institutions is the worst, and the fairness of geographical allocation of hospital bed resources is the worst; the unbalanced allocation of beds is mainly due to the uneven distribution in the region; the number of beds in medical and health institutions in the province has developed greatly, but the structure of bed resources is still unreasonable.

As shown in **Table 4**, during 2016–2020, the Theil index allocated by health institutions changed within the range of 0.015 to 0.02, with little fluctuation; from 2016 to 2018, the Theil index of health technicians, physicians, nurses, and bed allocation all showed an upward trend, but by 2019, its total Theil index began to decline significantly, while the Theil index for government health expenditure allocation from 2016 to 2020 showed a downward trend. It can be seen that the fairness of the allocation of various health resources in the province is improving year by year. Combined with the analysis of the total Theil index from 2016 to 2020, among all types of health resources, the allocation of nurses is the least equitable, and the allocation of health institutions and government health expenditures is relatively well-balanced.

TABLE 1 | The fairness ranking of various indicators of medical and health resource allocation.

	Gini coefficient by population distribution	Gini coefficient by geographical distribution
Health agency	1	1
Health technician	4	5
Practicing (assistant) physician	3	4
Registered nurse	6	6
Number of beds	5	3
Medical and health expenditure	2	2

TABLE 2 | 2015–2020 Theil index by region.

Years	Class I area	Class II area	Class III area	Citywide
2015	0.051	0.041	0.006	0.125
2016	0.075	0.006	0.201	0.265
2017	0.041	0.029	0.002	0.135
2018	0.061	0.021	0.004	0.098
2019	0.051	0.005	0.021	0.092
2020	0.042	0.002	0.022	0.086

Difference Index Evaluates the Fairness of the Allocation of Bed Resources in Our Province

The difference exponential fairness analysis of the allocation of bed resources in our province in 2020 is shown in **Figure 10**.

Analyzing the results of the above figure, it can be concluded that in 2020, the difference index of the allocation of beds in medical and health institutions in our province is 0.18

TABLE 3 | 2015–2020 Theil index of bed resource allocation and its decomposition.

Years	Interregional Theil index	Contribution rate (%)	Regional Theil index	Contribution rate (%)	Total difference
2015	0.025	19.22	0.086	80.78	0.125
2016	0.022	8.91	0.235	91.09	0.265
2017	0.036	29.98	0.071	70.02	0.135
2018	0.022	19.89	0.081	80.02	0.098
2019	0.028	29.78	0.061	70.22	0.092
2020	0.023	26.89	0.062	73.11	0.086

TABLE 4 | Theil index of health resource allocation.

Years	Health agency	Health technician	Practicing (assistant) physician	Registered nurse	Bed	Government health expenditure
2016	0.016307	0.043208	0.051012	0.069318	0.042118	0.013922
2017	0.017408	0.047082	0.053418	0.069819	0.040221	0.015913
2018	0.014307	0.054079	0.060122	0.073817	0.050223	0.009721
2019	0.018702	0.037209	0.030132	0.050122	0.039823	0.007211
2020	0.013609	0.017189	0.028326	0.041321	0.032019	0.003909

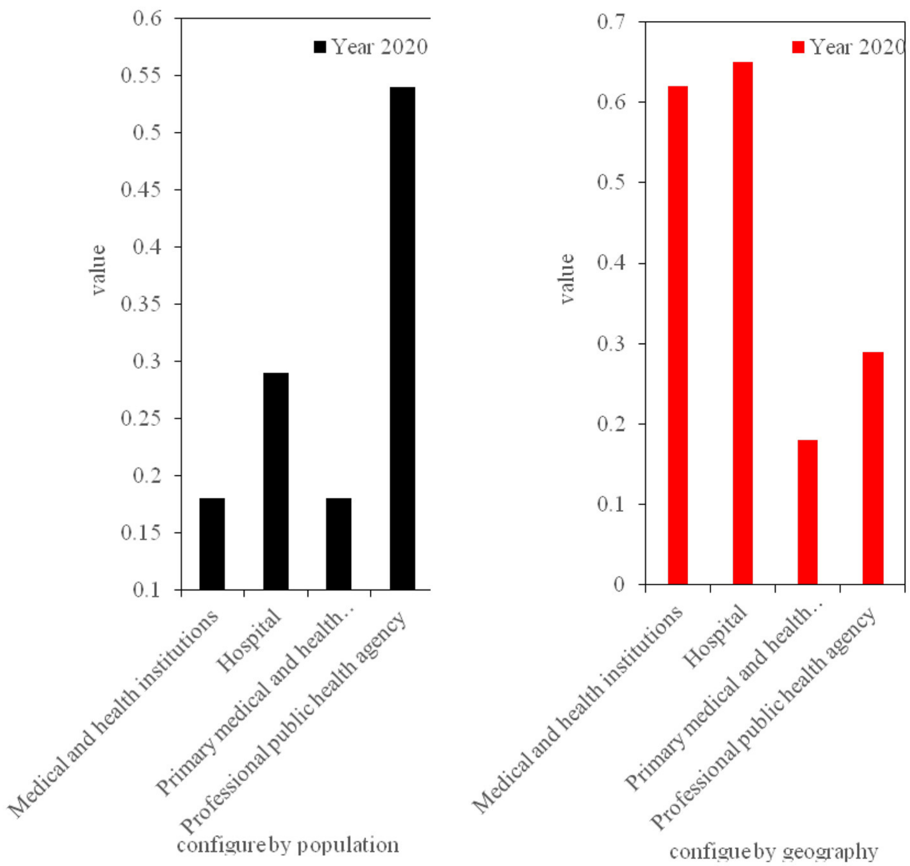

FIGURE 10 | Changes in the difference index of medical institutions.

by population and 0.62 by region; among them, according to population allocation, professional public health institutions have the largest difference in bed resource index, which is 0.54. According to the geographical distribution, the hospital bed resource difference index is the largest, which is 0.69. The resource difference index between beds in professional health institutions and hospital beds is relatively large, and its fairness needs to be strengthened.

CONCLUSIONS

This article mainly introduces the relevant theories of medical and health resource allocation. At the same time, it analyzed the allocation of health resources in the province in recent years. Through the Gini coefficient and the Lorentz curve, a statistical analysis of the population distribution and geographic area of our province was carried out, at the same time, the Theil index and the difference index were analyzed for the beds of medical institutions in this province. It was discovered that the province's health resources were unfairly allocated and irrationally allocated in the early stage, but they were improved later. And for this phenomenon, we should also take timely measures, adjust the resource structure, sink high-quality resources, and health administrative departments should explore scientific and reasonable resource allocation policies based on local actual conditions, and update resource allocation standards in a timely manner. Appropriately control the development speed of the hospital bed size, focus on the overall development of medical education and research, and enhance the overall strength; encourage new hospitals to focus on specialized hospitals such as rehabilitation, obstetrics and geriatrics, develop shortage of medical resources, and promote multidisciplinary development; adhere to the combination of prevention and prevention, integrate existing maternity and child health hospitals (institutions), occupational disease prevention and treatment hospitals (institutions) and other institutions, and construct a public health system that promotes and develops in coordination, better play the functions of disease prevention and health care and rehabilitation. In addition, the introduction of high-quality medical resources in the surrounding areas through the establishment of branch hospitals, new hospitals or upgrading the level of regional medical centers, etc. The focus of new high-quality resources tends to be the surrounding counties and cities with weak resources, and various methods such as raising the standard of bed allocation and increasing corresponding resource input to adjust the spatial layout of high-quality medical resources, improve the feasibility of medical services for residents in surrounding districts and counties.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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China's Hainan Free Trade Port: Medical Laws and Policy Reform

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In 2018, the government of China decided to develop Hainan Province as the country's first free trade port operating within the country's socialist system. Based on this strategy, Hainan reformed its medical laws and policies to make it freer and more open. For example, Hainan formulated policies for more rapid and convenient access of foreign medicine and sanitary equipment (MSE), allowed manufacturers to register MSE in China with real-world data (RWD), and provided legal and visa conveniences for international medical teams to carry out various activities, including: diagnosis, treatment and scientific research. Hainan's reforms are not only conducive to the improvement of local medical and public health levels, but also provide opportunities for international MSE manufacturers and medical research institutions swiftly to enter China's huge medical market. However, with opportunity comes risk: Hainan should be on guard against public health risks associated with medical tourism, and decide how to strike a reasonable balance between protecting local MSE enterprises and improving the accessibility of imported MSE through policies and legislation. Finally, the paper recommends that Hainan should improve the regulatory system as soon as possible to ensure the quality of diagnosis and treatment in its new hospitals, and deal with data and information security risks in the RWD research.

Keywords: Hainan free trade port, medicine and sanitary equipment, franchise, real-world data, shared hospitals

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INTRODUCTION

China is now the world's largest exporter and commodity trader (1). As an export-oriented developing country, the main threats facing China's economy are the decline in demand from its major trading partners and the rise of trade protectionism, which lead China to continue to pursue further opening up of its domestic market and the promotion of industrial upgrading (2). In pursuit of this goal, China proposes establishment of a new free trade port to compete with Dubai and Singapore (3). As the latest experiment in China's institutional innovation, the planned free trade port will be freer and more open than existing free trade areas in the country (4).

Earlier, China had put forward two cooperation initiatives: "Silk Road Economic Belt" and "21st Century Maritime Silk Road" in 2013 (known collectively as "The Belt and Road", B&R) (5). This new international economic cooperation framework aims to revive China's ancient trade route connecting Europe and Africa, to promote the economic growth of potential markets and improve the interconnection between China and these markets, in order to promote diversification of domestic trade and investment (6, 7). Based on the B&R initiative and the fact that more than 90% of China's foreign trade is borne by the sea, China chose Hainan Province, China's largest special economic zone, as an important node on the ancient Maritime Silk Road, and the location of the new free trade port, with the intention of making it an important hub connecting the Indian and Pacific Oceans (8, 9).

In 2018, China's President Xi Jinping announced that the country would build its first socialist system-based free trade port in Hainan Province. The aim was to develop it as a pilot zone for China's exploration of further reform and the opening-up of various fields (10). The central government has enabled the Hainan Free Trade Port (HFTP) to quickly gain a high degree of autonomy by reforming or revising relevant policies, administrative regulations and departmental rules. With autonomy, HFTP has carried out comprehensive reforms in various fields including finance, medical care, and immigration policies (3). Regarding medical issues, HFTP has issued a series of laws and policies designed to speed up the import of medicine and sanitary equipment (MSE), making foreign enterprises and social organizations significantly less restricted by policies or laws when they carry out trade and exchanges in HFTP compared to elsewhere in China (11). Finally, HFTP has promised within its jurisdiction to liberalize cutting-edge medical research (such as stem cell clinical research) (12).

It is worth noting that the reform efficiency of other free trade zones before HFTP was partly constrained by the speed with which the relevant laws were amended. This is mainly because China is a country with typical civil laws. Its legal system represents a hierarchical pyramid structure, with lower-level and local laws subservient to higher-level laws and without ability to exceed their authority (13). Revision of higher-level laws normally requires adoption by China's highest legislature, the National People's Congress (NPC), and this takes a long time (14). In order to ensure HTFP's reforms efficiency, the Standing Committee of the NPC promulgated the *Hainan Free Trade Port Law of the People's Republic of China* on June 10, 2021. The law granted Hainan Free Trade Port (HFTP) a high degree of legislative autonomy. According to Article 10 of the law, HFTP can suspend application of some national laws and regulations in the region and gained the right to formulate local laws in relation to special policies which are only applicable within the region (15). This unprecedented autonomy in legislation and policy-making is the biggest difference between HFTP and other free trade zones in China, which also provides legal protection for HFTP's reform measures in the medical field.

The reforms of HFTP are not only conducive to the improvement of medical and public health conditions in the region, but also provide guidance for China's future general reforms in related fields. This paper seeks to discuss the aspects of HFTP's reforms that have entered the practical stage and achieved certain results, to analyze the influences of the reforms on its medical and public health services, and to assess challenges linked to the reforms.

Abbreviations: MSE, medicine and sanitary equipment; RWD, real-world data; RWE, real-world evidence; B&R, the Belt and Road; HFTP, Hainan Free Trade Port; OPCHFTP, Overall Plan for the Construction of Hainan Free Trade Port; NMPA, National Medical Products Administration; NPC, National People's Congress; R&D, Research and development; RCT, randomized controlled trial; GIST, gastrointestinal stromal tumor.

SPECIFIC REFORM MEASURES IN HFTP

As shown in **Table 1**, the reform measures announced by HFTP in the field of medicine can be summarized in a framework comprising four modules: "Franchise Medical Care", "Franchise Operation", "Franchise International Communication", and "Franchising in International medical exchanges".

Due to insufficient time, some measures in the framework lack sufficiently clear practical results to test their effectiveness. In particular, travel restrictions caused by the Covid-19 pandemic brought many measures related to immigration policies, whereby "Franchising in International medical exchanges" almost came to a standstill. On the other hand, several of the reforms have already entered the practical stage and achieved certain results, including reform of optimizing MSE import mode, recognizing real-world data and attracting non-resident medical resources.

Making MSE Import Channels More Convenient

According to Articles 35 and 36 of the Regulations for Implementation of the *Drug Administration Law of the People's Republic of China*, a drug that has been marketed in another country must be confirmed safe, effective and clinically necessary by the National Medical Products Administration (NMPA) before it can be imported (16). To complete registration, pharmaceutical companies must carry out three phases of randomized controlled trials (RCTs) for several years. This makes it very difficult for new, specific drugs from abroad to enter China promptly (11).

In addition, while small quantities of urgently needed drugs can be imported by medical institutions for clinical use under legal authorization upon the approval of the NMPA, their use is restricted to specific medical activities in designated medical institutions (16). This means that patients can only be treated with urgently needed imported drugs in a specific medical institution, and cannot remove these drugs from a specific medical institution. When using urgently needed imported drugs which are crucial to a patient's treatment, they must be hospitalized in accordance with the regime determined by the specific course of treatment. This significantly increases the duration, cost and financial burden for patients.

China's central government has authorized HFTP to independently approve the import of MSE within its region (16). As a result, HFTP allows related enterprises to freely apply to import MSE already marketed in developed countries within its region, (17). The average approval period is between three and seven days (18). Some low-risk MSE can enter a HFTP bonded warehouse prior to the declaration process (19), which reduces to one day the time from application to use of imported MSE. Additionally, HFTP is vested with the right to apply to the Ministry of Finance to adjust some MSE tariffs annually according to demand (20).

The drug ripretinib is a successful example of HFTP's reform. It is the latest specific drug for the treatment of gastrointestinal stromal tumor (GIST) (21). Annually, in China there are about 30,000 newly diagnosed GIST cases and over 100,000 GIST patients receiving treatment (22). Outside the HFTP, it can take

TABLE 1 | The reform measures announced by HFTP in the field of medicine.

Franchise Medical Care	1. MSE that is listed abroad but not domestically can be used in a small range of medical institutions within HFTP. 2. Set up a special import MSE review scoring center in HFTP to simplify the evaluation process of its licensed imports. 3. Patients from medical institutions in HFTP can leave with a reasonable amount of licensed imported MSE. 4. The RWD generated by imported MSE in HFTP can be collected and used for medical research and MSE registration in China. 5. Members of public hospitals and medical institutions in other parts of China can be licensed to practice part-time in HFTP.
Franchise Operation	1. Well-known hospitals can authorize their brand, trademark, technology, management, etc. to medical institutions in HFTP for use, 2. Imported monoclonal antibodies and other low-risk special items are subject to "warehouse first, quarantine later". 3. Remove restrictions on foreign shareholding in health insurance and life insurance companies within HFTP.
Franchise International Communication	1. Research on cutting-edge medical technologies such as stem cells and their transformational applications can be carried out in HFTP. 2. Overseas research institutes and medical colleges can establish branches in HFTP according to law.
Franchising in International medical exchanges	1. Foreign medical staff can carry out medical activities in HFTP according to law, and can apply for a work-type residence permit consistent with the working period. 2. Family members of foreign patients can apply for private affairs visas or residence permits during the patient's medical service period. 3. Overseas manufacturers can set up after-sales centers in HFTP to provide after-sales services for MSEs that are used in HFTP but have not yet been registered in China.

years before the drug is allowed to be used in the treatment of patients in China. In HFTP, however, approval for small-scale use of ripretinib followed within 2 months after the drug achieved global approval in May 2020. As a result, ripretinib became the first new drug that Chinese patients could receive at the same time as patients elsewhere in the world (23). In addition, HFTP allows patients to leave medical facilities each time with drugs for one course of treatment, which effectively cuts down tariff costs (24).

Real-World Data (RWD) Can Be Used for MSE Registration

MSE is the cornerstone for promoting good public health. Clinical evidence of evidence-based medicine, a new model of modern clinical practice and research, mainly comes from large-sample RCTs and meta-analyses (25). However, due to the current lack of sound mutual recognition mechanism for foreign RCTs, it may take years to conduct RCTs before a foreign MSE can enter the Chinese market.

RCTs are currently the recognized standard for evaluating the efficacy of MSE in countries around the world (25). RCT results are generally required for the approval of MSE registration and marketing and for the addition of indications after marketing. With the development of evidence-based medicine, however, the RCTs' limitations have gradually become clear. First, the research conclusions of RCTs may be challenged via experiences in clinical practice. Due to strict inclusion and exclusion criteria, a trial population cannot fully represent the target population, but only reflect the efficacy of MSE in specific situations. The standard intervention adopted may not be completely consistent with clinical practice. Moreover, the limited sample size and short follow-up time result may lead to underestimation of rare adverse events. Second, research resources are very limited for some rare or infrequent diseases and, as a result, it is difficult to carry out traditional RCTs. As a result, enterprises may reduce interest in research investment, considering the limited economic benefits. Third, traditional RCTs generally demand considerable investment of time and money (26).

In recent years, real-world study (RWS) has attracted increasing attention. RWS is based on the premise of non-intervention, that is, where treatment measures are non-randomly selected according to the actual condition and wishes of patients. Data related to the MSE used and the health status of patients (i.e., RWD) is then collected and analyzed. Conclusions are drawn from evidence from large samples, long-term evaluation and statistical analysis, so as to obtain data on evidence-based medicine for MSE. The purpose is to ascertain its medical effectiveness, that is, sufficient real-world evidence (RWE) (27). In 2016, the *21st Century Cures Act* was passed in the USA, which authorized the US Food and Drug Administration to use RWD, where appropriate, as the approval evidence for post-market research and new indication development of MSE (28).

Currently, RCT data are still required in Chinese law for the application of registration and marketing of MSE or the addition of indications for MSE. However, with the support of the central government, HFTP has suspended the application of the relevant provisions in the current *Regulations for the Supervision and Administration of Medical Devices in the region.* Hainan has promulgated the *Implementation Plan of the Pilot Work of Clinical Real-World Data Application in Hainan Boao-Lecheng Pilot Zone of International Medical Tourism*. According to this policy, MSE without registration in China can be imported and used on a small scale in the region after being licensed. The clinical data generated during the use of licensed MSE can be converted into RWD and RWE for registration and approval in China after scientific and strict design, collection, processing, analysis and evaluation (29).

The above reform not only offers a legal way for Chinese patients to quickly obtain imported MSE, but also significantly increases the speed of foreign MSE entering the Chinese market.

For example, after Allergan obtained RWD for its product "XEN Glaucoma Treatment System" in HFTP, the RWE acquired by the analysis successfully passed the marketing approval of NMPA. The process took fewer than 5 months overall, while the product registration cycle was seven times shorter (30).

Attracting Non-resident Medical Resources Through "Shared Hospitals"

As the only tropical island province in China, Hainan has long been famous for tourism not its medical industry. Once HFTP's medical and public health resources were chronically inadequate. For example, in July 2018, Hainan, with a resident population of about 9.257 million, had only 1,094 general practitioners, that is, an average of only 1.18 general practitioners for every 10,000 people (31).

Moreover, restricted by China's relatively strict physician management system, it was difficult for HFTP to gain much in the way of physician resources in a short period. Currently, the practice qualification of physicians is tied to their medical institutions. In the past, physicians in some economically developed areas with abundant medical resources in China (such as Shanghai) were allowed to travel to other regions for treatment on a personal basis. However, the central government discovered that this regime of diagnosis and treatment bred medical corruption. For example, some physicians began to neglect their duties and sought to practice medicine under their own names so as to generate higher incomes (32). In response, in 2005 the Chinese government promulgated the Interim Provisions on the Management of Physicians' Outing Consultation. The aim was to prohibit private diagnosis and treatment. According to the Provisions, physicians are not allowed to carry out medical activities under their personal name, while cross-regional and cross-institutional diagnosis and treatment can only be undertaken with the agreement of relevant institutions (33). Income from such diagnosis and treatment cannot be paid to the physician directly, but is realized by the hospital where he or she practices via a reasonable increase in wages during the same period (33).

In response, HFTP experimented in becoming a platform provider which "does not ask for ownership, but for use" rather than a resource owner. HFTP also established a new type of "shared hospital" (34), responsible for formulation of a management system, daily supervision, MSE procurement and other management and operation activities. Medical teams from outside the HFTP region can be stationed in the hospital as specialists. They are not required to be resident in Hainan and are able to conduct diagnosis and treatment in the hospital when there is a medical need. All medical teams have equal paid sharing of hospitals' imaging diagnosis centers, surgery centers, hospital beds and other resources. Financial settlement is at their own risk. The MSE needed for diagnosis and treatment, but without registration in China, can be acquired through licensed imports. Benefiting from HFTP's liberal immigration policy, medical teams from other countries and regions other than the Chinese mainland can also apply for admission to the hospital for business reasons.

DISCUSSION

In general, HFTP has quickly carried out a large number of reforms in the medical field, providing increased convenience and preferential policies for medical resources from other regions or countries to enter China. This has also had positive impacts on the public health status of HFTP. On the other hand, HFTP's reforms also face significant challenges.

HFTP's Medical Laws and Policy Reforms: Positive Outcomes

HFTP has limited local medical resources with a per capita gross domestic product of fewer than 10,000 US dollars (35). This makes it in the short term difficult to invest heavily in health care and public health. As a result, carrying out institutional reforms to encourage entry of extra-regional capital and medical resources is a realistic option for HFTP. The current effect is that the greatest significance of the reforms is to make HFTP the most open region for the Chinese mainland to import MSE and foreign medical teams.

Such openness offers HFTP residents the opportunity to enjoy the latest MSE in line with the international market and the expertise and resources of advanced medical teams from other countries and regions. Due to the high-level of tariff autonomy in HFTP and the good quality and low cost of medical infrastructure in the region, the prices of related MSE and diagnosis and treatment services has been significantly reduced, effectively lowering patients' treatment costs. For example, the cost of Boston keratoprothesis in HFTP is roughly 14% of that of similar operations abroad (36).

HFTP's openness is also conducive to the improvement of the health status of some disabled people. For example, the specific MSE urgently needed by some disabled people with rare diseases (such as multiple sclerosis) is not produced in the Chinese mainland. To enter China's market (37), this type of foreign MSE must go through three phases of RCTs. As a result, it is difficult for affected disabled people to obtain such medication. However, the open and more human-oriented medical policies of the HFTP greatly reduce the time and economic costs for the above-mentioned MSE to enter HFTP. This increases the accessibility of the latest international MSE in the region (38). Considering that disabled people are often economically poorer than healthy people (13), then reducing their rehabilitation costs helps to achieve greater health equity in HFTP.

In addition, the reform of HFTP also offers good opportunities for international pharmaceutical enterprises. China's total health spending reached ￥6.5196 trillion in 2019 (about US$1.0073 trillion based on the current exchange rate) (39), making it the world's second largest single-country health market. In the context of the COVID-19 pandemic, based on the latest outlook report of the World Bank, the growth of the world's major economies declined, yet China's economy was expected to grow by 8.5% in 2021 (40). This suggests that China would currently be one of the most vibrant economies in the world. Reform of HFTP not only provides a liberal and convenient licensed import channel for international MSE, but also significantly speeds up the official registration of licensed MSE in China by collecting and licensing RWD. Therefore, HFTP has become the best channel for global MSE to rapidly enter the huge Chinese market.

HFTP's Medical Laws and Policy Reforms: Challenges

The reform of HFTP faces many challenges. In the current stage, medical tourism-associated public health risk is the major challenge facing the fields of medical and public health. HFTP has established nine new hospitals in Boao Lecheng, including two stem cell hospitals whose main business is anti-aging treatment (41). Due to the good rehabilitation environment of the tropical island in HFTP and the convenience of licensed MSE imported by new hospitals, HFTP is the most prosperous medical tourism market in China (42). However, the boom in medical tourism may introduce additional public health risks. So far, evidence suggests that the growing popularity of medical tourism in the USA has resulted in an increased infection rate of nontuberculous mycobacteria among its citizens (43). This suggests that the issue of additional public health risks should also be taken seriously by the authorities in HFTP. At present, the HFTP Law requires HFTP in Article 12 to strengthen public health security at ports (44). HFTP should make as soon as possible targeted law and policy for the additional public health risks that may increase from medical tourism.

Second, the acceleration of foreign MSE imports has also brought new challenges to the field of intellectual property management of HFTP. From 2012, China promised to implement stricter intellectual property protection, rapidly revise a series of laws and regulations such as the patent law, and establish new specialized intellectual property courts, one of which is located in HFTP (45) Thanks to these measures, HFTP's intellectual property management system has improved. However, the challenges faced by HFTP in the field of intellectual property management come from within, that is, a lack of sufficient professionals (46). In general, officers engaged in MSE intellectual property management should be familiar with relevant laws and policies of China's intellectual property management system and have a basic understanding and an appropriate level of professional knowledge (in, for example, biology or chemistry). This requires a relatively high level of education. However, Hainan is short of people with relevant higher education: as of 2020, only 13.92% of Hainan's total population had received a college education or above (47). Before the central government decided to establish HFTP, the lack of talents was not an urgent problem in Hainan. Hainan was only an island province dominated by tourism and its service industries, and the workload of intellectual property management was not large. Data disclosed by Hainan Province showed that by the end of November 2015, Hainan province had only 2,074 valid invention patents (48). In comparison, Huawei, a well-known technology company in China, had 87,805 patents in early 2018 (49). However, HFTP's reform will likely make Hainan the first choice for overseas MSE to enter the Chinese market. This implies that the number of MSE patent applications and intellectual property disputes in HFTP may surge. HFTP has realized that it is facing a key challenge: serious shortage of MSE intellectual property management talents (50). In response, HFTP has launched an unprecedented talent introduction plan, which aims to bring in on favorable terms more than a million people with professional and technical talents, including expertise in intellectual property management, from other regions at home and abroad (46). We will pay close attention to the effectiveness of the plan.

Third, the operation mode of shared hospital may have a negative impact on its diagnosis and treatment quality. A shared hospital provides a new hospital business model. It also means that a shared hospital will be composed of dozens of non-resident teams that do not necessarily relate easily to each other. For example, teams and hospitals will have less experience in daily cooperation and work docking than traditional hospitals. Unfamiliar cooperation and differences in work habits may lead to an amplification of avoidable medical mistakes. For example, in January 2021, a patient died while undergoing cochlear implantation surgery in a shared hospital. His family then pointed out that there were a series of avoidable low-level technical errors in the diagnosis and treatment process at the hospital, including the wrong recording of the patient's age and medical history (51). Perhaps because the shared hospital only provided a medical platform for resident teams, these errors were not found and corrected during the diagnosis and treatment stage. This tragedy suggests that HFTP needs to think swiftly about establishing a more effective supervision system for shared hospitals.

Fourth, the collection and application of RWD brings new regulatory challenges for HFTP in terms of data and information security. HFTP approved the reform measures of RWD, which have greatly improved the registration and listing speed of MSE. However, compared with the mature regulatory system of RCT in China, the regulatory system for RWD in HFTP is still not perfect. In terms of data and information security, HFTP requires all parties involved in RWD research to conduct security processing on data (especially data involving personal privacy) and establish a robust data security management system (52). However, these provisions may seem too principled and lack sufficient consideration of the details that may arise at the practical level. For example, the policy document of HFTP only requires the anonymization of relevant data, and does not specify who should be responsible for this activity in the study. Neither does it specify at which stage of the RWD study this step, which is critical to patient privacy, should be carried out. This means that researchers may have the opportunity to obtain from the hospital original data that has not been anonymized, which may increase the risk of patient privacy data disclosure. In addition, HFTP has not yet made detailed provisions on the legal liability of enterprises for RWD leakage, damage or loss due to accidents or other reasons. In short, HFTP urgently needs to further refine the relevant principled provisions on RWD.

Another concern is that the rapid introduction of foreign MSE may impact on local enterprises' R&D and production. Currently, there is still a big gap in MSE R&D and production capacity between Chinese enterprises and western counterparts (53). Although simplification of the procedures for the introduction and registration of foreign MSE by HFTP increases the accessibility of MSE, it also brings significant competition between local enterprises and large international enterprises. This should not be ignored. For example, since the marketing of the trastuzumab antibody drug conjugate DS8201 characterized by high cell membrane penetration and high portability in the USA in 2017, it has shown high efficacy in the posterior line treatment of a variety of tumors (such as advanced breast cancer) with overexpression or mutation of HER2 (54). However, in China it is only accessible in Hong Kong. For similar drugs that have been marketed in the mainland, the progression-free survival time of patients in posterior line treatment is inferior to that of patients taking DS8201: that is, 12.5 vs. 19.7 months in advanced breast cancer with the median treatment line of 6 (55). If DS8201 could enter the Chinese market quickly and at a low cost through the HFTP channels, the products produced by related enterprises of China would be very uncompetitive, and such enterprises would be deleteriously impacted.

However, we believe that HFTP's reform policy of accelerating the import process may have deepened the inferior position of Chinese enterprises in some areas, but this may be within the country's previous plans. At present, HFTP is mainly licensed to import MSE that is difficult for China to achieve domestic substitution in a short time. Most are specific drugs for the treatment of cancer and rare diseases. China Customs has previously reduced the tariff rate of these two types of MSE to 0% (56). It seems clear that China's tariff policy is the main reason why local companies face fierce competition in this field. HFTP's reform has not brought new adverse factors to the local pharmaceutical industry, but only intensified existing competition. Such difficult decisions are related to China's ambitious goal of raising the life expectancy of its 1.3 billion people by an additional year during the 14th Five-Year Plan period (2021–2025) (57). At a time when there is a significant difference between the efficacy of domestic MSE and imported MSE, China has had to temporarily sacrifice some interests of local enterprises in order to improve the drug accessibility for cancer and rare disease patients in order to improve per capita life expectancy. However, China has put forward the "Made in China 2025" strategic plan to help relevant companies further improve the level of MSE research and accelerate the process of localization of MSE, so as to support local companies currently disadvantaged (56). As a result, we believe that China still adheres to the policy of strengthening scientific and technological autonomy in the field of medicine and supporting domestic substitution. In this process, China hopes to reduce the medical burden of domestic patients through HFTP reforms in areas where domestic MSE is temporarily powerless. Although the impact of HFTP reform on local companies does not currently exceed China's expectations, considering the freer and more open development goals of HFTP, its special approval policy for imported MSE may be further expanded. The question remains: how to strike a reasonable balance between protecting production and R&D of local MSE and increasing accessibility of international MSE?

Overall, the reform of HFTP in the medical field is still in its infancy and faces many challenges. This paper has argued that HFTP's reforms in the medical field face more institutional challenges than reforms in various areas, including finance and taxation. This may relate to the lack of a mature domestic system template for HFTP's reform in this field. China has not yet formulated a systematic health law. The current health legal system is composed of more than 30 old and new laws. The lack of coordination between laws and sometimes conflicting situations still occurs, making it difficult to provide a systematic legal template for the reform of HFTP (58). In addition, HFTP law is mainly a principled authorization law that does not provide for more detailed provisions on the reform plans of HFTP. At present, the main roadmap of HFTP's reform is the *Overall Plan for the Construction of Hainan Free Trade Port* (OPCHFTP) issued by the central government, although OPCHFTP makes a few principled provisions, such as:

> "We should support Hainan in introducing high quality foreign medical resources from abroad. We must draw from the trial experience of regional medical centers to explore and support the building of regional medical centers in Hainan" (59).
>
> –Article 12, Section 1,Chapter III, OPCHFTP

In the absence of a systemic template, HFTP must try to construct a new institutional concept and framework for its medical reforms. While this implies that HFTP's reform may face additional unexpected challenges, as stated in OPCHETP, HFTP's reform experience and lessons in this field will still become an important reference for national reforms (59).

CONCLUSION

HFTP is called "the pilot zone of national reform and opening up" by the Chinese government (60). This means that the successful experience of HFTP's reform is likely to be extended to other parts of China by the central government. Currently, the institutional reform of HFTP enables it to effectively increase the accessibility of imported MSE and the openness of the medical industry without excessive investment by the authorities. This may mean that China is probing how to further open up its huge medical market to improve its medical and public health standards. However, based on China's past reform experience, the often-cautious central government might consider carrying out similar reforms in other parts of China—but only after HFTP has both undertaken sufficient trial and error measures in relevant fields and improved the reform plan until it is seen to be economic, feasible and risk-controllable. As a result of such concerns, the reform of medical laws and policies in HFTP will necessarily be long-term and in-depth. This would not only bring major benefits for patients both in HFTP and elsewhere in China, but also provide an excellent opportunity for relevant international enterprises and institutions quickly to enter China's market. However, HFTP should form a systematic policy and legal framework in the health sector as soon as possible, and further improve supervision capabilities to ensure the stability and long-term nature of reform measures.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

All authors made a significant contribution to this work, in relation to the conception, study design, execution, acquisition of data, analysis, and interpretation. All authors were involved in drafting, revising or critically reviewing the article, and gave final approval to the current version. Finally, all agreed on which journal the article should be submitted to and are accountable for all aspects of the work.

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When Does Da Vanci Robotic Surgical Systems Come Into Play?

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The emergent of medical science and technology has risen the minimally invasive surgery. Da Vinci Robotic Surgical Systems (RSS) is the trend at present. Compared with the past surgical methods, many studies related to RSS tend to explore postoperative outcomes and quality of life or compare the advantages and disadvantages than the other surgery. Few studies to understand the patients' willing who use RSS. This study mainly explores the patients' willingness and adopts the Technology Acceptance Model (TAM) as the theoretical foundation, and appended the trust concept to discuss. The study was a retrospective study and used a structured questionnaire to conduct a survey. The subjects included the patients with single-disease who had used RSS in a Medical Center of Southern Taiwan but excluded the patients with multiple disorder. This study conducted SPSS 22.0 and Smart PLS 2.0 software for statistical analysis, which included descriptive statistical analysis and applied Partial Least Squares (PLS) analysis to test the research model and to examine the established hypotheses. A total of 136 cases were collected in this study. Study validation was tested. Trust positively affects Perceived Usefulness ($\beta = 0.550$) and Perceived Ease of Use ($\beta = 0.300$). Perceived Ease of Use positively affects Perceived Usefulness ($\beta = 0.188$). Perceived Usefulness positively affects Attitude Toward Using ($\beta = 0.589$. Attitude Toward Using positively affects Behavioral Intention ($\beta = 0.446$. The relationship between perceived Ease of Use and Attitude toward Using was insignificant. Additionally, the relationship between Perceived Usefulness and Behavioral Intention was insignificant. In the research results, we found that patients are mostly in the middle and high age groups, and if the patient himself feels that RSS is extremely helpful to his illness, the intensity of his choice of intention will be high. In comparison, the information related to RSS has been clearly known, it does not directly affect the selection intention. According to age, most of the choices of RSS is based on safety and risk considerations, and it is beneficial to the patient himself, but RSS is also more expensive. We recommended that the government consider $\beta\beta$ reimbursing the RSS process in health insurance programs to meet the needs and expectations of patients.

Keywords: robotic surgical systems, technology acceptance model, trust, intention, surgical methods

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INTRODUCTION

The rapid development of medical technologies, along with improvements in medical standards and the rise of patient awareness has driven the evolution of traditional large-incision surgical practices to the development of Minimally Invasive Surgery (MIS) which minimizes incision size, blood loss and post-surgical pain (1–4). MIS practices have subsequently driven the development of Robotic Surgical Systems (RSS), which aim to improve on Conventional Laparoscopic Surgery (CLS), reduce natural tremor, and improve surgical accuracy and vision (5). These technical advantages lead to improved clinical outcomes, including reductions in postoperative complications and shortening the length of hospital stay (6).

There are very complex environments and problems in the health care system. To improve the efficiency and quality of healthcare, it often uses the development of emerging technologies and innovative medical methods, such as RSS. The current research on RSS has focused on patient safety skepticism, body dissatisfaction, and other inconsistent research results, leaving a research gap into factors that may influence patient willingness to undergo RSS (7, 8). The present study attempts to establish a prediction model for patient acceptance of RSS. Facing new medical technologies, patients usually want a voice in their medical decision-making (9–11). Previous relevant research on patient views on surgery and patient satisfaction mainly focused on the patient's perception of the degree of success of their surgery or how various surgical factors affect patient decision-making (12, 13). However, few such studies examine patient views on emerging medical technologies, especially patient decision-making and intention to adopt new surgical technologies.

Past studies have found that RSS does reduce the consumption of postsurgical medical resources, and reduces postsurgical complications, thus reducing the need for blood transfusions, respirators, and intensive care, and shortening the length of hospital stay (14, 15). The introduction of RSS also helps address the shortcomings of CLS. However, RSS is still subject to certain limitations, such as high surgery-related expenses. Seeking to increase competitiveness and avoid patient loss, hospitals are increasingly investing in RSS, taking on additional repair and maintenance costs (16, 17). This increased investment requires hospitals to maximize the use of RSS equipment, resulting in supply-induced demand and a tense relationship between physicians and patients. In addition, patients generally suffer from medical information asymmetry, leaving them unable to effectively participate in decision-making regarding their care, and thus increasing their dependence on clinicians to make critical choices (18, 19). Different patient conditions require different surgical approaches, and the choice of any particular surgical method must be carefully considered. However, the patient's lack of access to complete information leaves them little choice but to trust their physician's judgement (20, 21). More discussion is needed on the factors that patients consider when deciding to adopt RSS.

To understand these influencing factors and decision-making considerations, we apply Davis' (1989) Technology Acceptance Model (TAM) to explore the behavioral intentions of users faced with a new technology system (22, 23). This model seeks to predict and explain the factors affecting user behavior in accepting new technologies, and to explore the influence of external variables on users' personal beliefs, attitudes and intentions (24). Personal beliefs include perceived usefulness (PU) and perceived ease of use (PEOU). This study applies TAM to perform an in-depth exploration of patients' willingness to undergo RSS, coupled with the previously mentioned factors of information asymmetry and medical decision-making power asymmetry, and trust (25).

Deutsch (1962) noted that the concept of trust is at play in many fields, including the integration of science and technology acceptance models to explore the relationship between trust, PU and PEOU (26). In addition, knowledge sharing is also the key to team work (27). Trust is defined as a connected psychological state between people. In this state, people expect to cooperate with each other, giving them faith in the behavior of the other party, even in cases of uncertainty. Thus, in medical situations, the patient trusts that the medical care provider is genuinely concerned with his/her interests, and thus has the confidence necessary to accept treatment methods that may entail risk (28). In the current medical model, the physician is the key leader and decision-maker, and the relationship between physician and

TABLE 1 | Descriptive analysis ($N = 136$).

Variables	Contents	*N* (%)
Gender	Male	114 (16.2)
	Female	22 (83.8)
Age	31–49	9 (6.6)
	50–65	41 (30.1)
	66–75	58 (42.6)
	Over 75	28 (20.6)
Education	12th grade or less	55 (40.4)
	Graduated high school or equivalent	36 (26.5)
	Bachelor's degree	38 (27.9)
	Master degree or above	7 (5.1)
Medical specialist	General surgery	45 (33.1)
	Urology	86 (63.2)
	Colorectal surgery	5 (3.7)
Occupation	Medical	3 (22.0)
	Military government	32 (23.5)
	Service	91 (66.9)
	Agriculture	10 (7.4)
Disposable income (US)	1,000–2,000	89 (65.4)
	2,000–3,000	26 (19.1)
	3,000–4,000	12 (8.8)
	4,000–6,000	6 (4.4)
	Over 6,000	3 (2.2)
Operation experience	Yes	81 (59.6)
	No	55 (40.4)
Robotic surgery experience	Yes	14 (10.3)
	No	122 (89.7)

TABLE 2 | Mean and standard deviation for measurement items.

Construct dimension	Measurement question	Mean ± SD
Trust	(Trust1) The doctor is very knowledgeable about Da Vinci surgical treatments and techniques.	4.85 ± 0.51
	(Trust2) The doctor can provide treatments that meet my needs according to my condition.	4.85 ± 0.45
	(Trust3) The doctor can fully explain to me the recovery process and postsurgical conditions.	4.85 ± 0.45
Perceive of usefulness (PU)	(PU1) Da Vinci surgery will allow me to recover quickly after surgery.	4.94 ± 0.24
	(PU2) Da Vinci surgery can relieve my pain.	4.95 ± 0.22
	(PU3) Da Vinci surgery result in a smaller and more aesthetically pleasing incision scar.	4.91 ± 0.31
	(PU41) Da Vinci surgery will reduce postoperative complications.	4.76 ± 0.55
	(PU5) Da Vinci surgery is safer than other surgical treatments.	4.82 ± 0.52
Perceive ease of use (PEOU)	(PEOU1) I clearly understand the advantages and disadvantages of Da Vinci surgery.	4.35 ± 0.81
	(PEOU2) I clearly understand the difference between Da Vinci surgery and other surgical methods.	4.46 ± 0.79
	(PEOU3) I clearly understand that Da Vinci surgery is not covered by Taiwan's National Health Insurance, and I will have to pay out of pocket.	5.00 ± 0.00
	(PEOU4) Information about Da Vinci surgery is easily accessible.	4.25 ± 0.86
	(PEOU5) I can easily ascertain the differences between Da Vinci surgery and other surgical techniques for the same condition.	4.25 ± 0.88
	(PEOU6) I have easy access to information on the advantages of Da Vinci surgery for my specific condition.	4.33 ± 0.84
Attitude (ATU)	(ATU1) Da Vinci surgery is the right choice for me.	4.85 ± 0.41
	(ATU2) Da Vinci surgery is effective.	4.82 ± 0.46
	(ATU3) Da Vinci surgery is a voluntary choice.	4.99 ± 0.12
	(ATU4) The selection of robotic surgery is under consideration.	4.62 ± 0.74
Intention (INT)	(INT1) I am willing to use Da Vinci surgery for treatment.	4.99 ± 0.12
	(INT2) If the symptoms of the disease are suitable and the doctor's skills permit, I will specify the use Da Vinci surgery.	4.76 ± 0.58
	(INT3) I think it is worthwhile to use Da Vinci surgery.	4.86 ± 0.43
	(INT4) I would recommend Da Vinci surgery to others.	4.87 ± 0.44

patient is based on mutual trust (29). The patient's trust in the doctor can be regarded as an important factor to create improved interaction and increase the patient's participation in treatment decision-making so as to jointly decide with the doctor the most suitable treatment given the patient's specific conditions (25). Based on this, this study uses "trust" as an external variable in the technology acceptance model to explore patients' willingness to choose RSS, and whether the patients' trust in physicians will affect the patients' personal beliefs, including regarding the relationship between PU and PEOU.

Therefore, based on the above research background and motivation, this study uses TAM as the theoretical basis to explore the behavioral willingness of patients to choose RSS. Retrospective research is used for data collection, and Partial Least Square (PLS) is used to verify and analyze the research model to explore the relationship and influence between the external variable trust with PU, PEOU and other aspects in TAM (30).

METHODOLOGY

Based on the research background, motivation and related literature discussion, this study establishes a research framework to explore patients' willingness to use RSS. The research is based on the TAM proposed by Davis (1989), and considers that the RSS will be performed by the physician using the Da Vinci robotic surgical system. Therefore, the external variable Trust is added to explore the relationship between PU, PEOU, Attitude, and Intention.

This retrospective study collected data by questionnaire with Institutional Review Board (IRB) approval. The sample was collected from November 2017 to July 2018, from a medical system in southern Taiwan using RSS to treat patients for a single condition. Data was collected by structured questionnaire from patients receiving hepatobiliary, pancreatic, urological and colorectal surgery. Patients receiving treatment for multiple conditions were excluded. The final sample included a total of 136 patients. The contents of the questionnaire were explained to each patient and informed consent was secured. The questionnaire was designed based on the research purpose, past research and theoretical considerations. The questionnaire was divided into two parts, including "Patient characteristics" as the categorical variable, and "Main Questions" scored on a 5-point Likert Scale, wherein 1 = strongly disagree and 5 = strongly agree. To avoid ambiguity and unclear language in the questionnaire content which may adversely affect response validity, the researchers reviewed the questionnaire wording with two questionnaire development experts, three clinicians with RSS experience, and three teaching hospital administrators, with content validity quantified based on the Content Validity Ratio

TABLE 3 | The CR and Cronbach's α for constructs.

Constructs	Items	CR	Cronbach's α
Trust	3	0.820	0.670
PU	5	0.863	0.801
PEOU	6	0.848	0.856
INT	4	0.744	0.670
ATU	4	0.759	0.688

TABLE 4 | Convergent validity analysis results.

Constructs	Item	Factor loading	AVE
Trust	Trust1	0.573	0.611
	Trust2	0.885	
	Trust3	0.849	
PU	PU1	0.726	0.558
	PU2	0.800	
	PU3	0.642	
	PU4	0.758	
	PU5	0.799	
PEOU	PEOU1	0.729	0.634
	PEOU2	0.762	
	PEOU3	0.000	
	PEOU4	0.751	
	PEOU5	0.848	
	PEOU6	0.899	
ATU	ATU1	0.902	0.626
	ATU2	0.882	
	ATU3	0.510	
	ATU4	0.188	
INT	INT1	0.231	0.643
	INT2	0.524	
	INT3	0.949	
	INT4	0.885	

TABLE 5 | Discriminant validity results ($N = 136$).

Constructs	Trust	PU	PEOU	INT	ATU
Trust	1.000				
PU	0.606*	1.000			
PEOU	0.299	0.351	1.000		
INT	0.591	0.546	0.330	1.000	
ATU	0.532	0.628	0.309	0.607	1.00

**The root square of AVE for constructs.*

(CVR). Based on expert input, the questionnaire was modified to meet content validity standards (31, 32).

SPSS 22.0 and Smart PLS 2.03 were used for statistical analysis, including descriptive statistics and PLS. Descriptive statistics mainly analyzed the basic patient data, including gender, age, medical department, education background, economic status, occupation, prior surgical experience and prior use of Da Vinci surgery. PLS is divided into two stages: measurement model analysis and structural model analysis. Measurement model reliability and validity are assessed using the PLS algorithm, and Bootstrapping is performed to generate the path coefficient β value and *t*-value to assess statistical significance. PLS-SEM is based on regression as an analytical approach. It focuses on the explanatory power (R^2) rather than model fit. Bootstrapping is a type of non-parental statistical inference based on resampling to makes statistical inferences when the distribution of the original population and the distribution of data sources are unknown (33).

The measurement model analysis verifies whether each theoretical measurement variable can accurately measure the potential variables, and whether there are complex measurement variables that load different potential variables, thus verifying internal consistency and construct validity. Construct Validity includes Convergent Validity and Discriminant Validity. The former refers to variables from the same dimension, which have a high degree of mutual correlation; the latter refers to variables from different dimensions, which have a low degree of mutual correlation. Structural model analysis includes analysis of the explanatory power of model fit and overall research modeling. The former tests the degree of fit between the overall research model and the observed data; the latter refers to the causal relationship between the potential variables in the model.

RESULTS

This study sample includes a total of 136 patients, including 114 males (83.8%) and 22 females (16.2%). Of these, 81 (59.6%) had previous surgical experience, and 14 (10.3%) had previously undergone Da Vinci robotic surgery system. **Table 1** summarizes descriptive statistics for the sample as well as **Table 2** shown means and standard deviations for measurement items.

In the reliability and validity analysis, the composite reliability (CR) value of each dimension of this study does not fall below 0.5 and thus meets the standard. **Table 3** shows the CR and Cronbach's α values of each dimension. Convergent Validity refers to whether the questionnaire items in each facet can converge based on factor loading (FL) and the average extraction variance (AVE) for each facet, where the FL and AVE values for all items should exceed 0.5. **Table 4** shows the Convergent Validity analysis results. This study was conducted using the method proposed by Chin (1998), in which discriminant validity is demonstrated by the square root of AVE of each facet exceeding the correlation coefficient between the facets (34). The results are shown in **Table 5**.

This research establishes 5 hypotheses as follows: Trust positively affects PU ($\beta = 0.550$, $T = 4.527$), Trust positively affects PEOU ($\beta = 0.300$, $T = 4.579$), PEOU positively affects PU ($\beta = 0.188$, $T = 2.242$), PU positively affects ATU ($\beta = 0.589$, $T = 4.835$), and ATU positively affects BI ($\beta = 0.446$, $T = 2.416$). Two hypotheses are found to not be statistically significant and are thus not supported, namely PEOU and ATU, PU and BI. **Figure 1** shows the verification of the research model path.

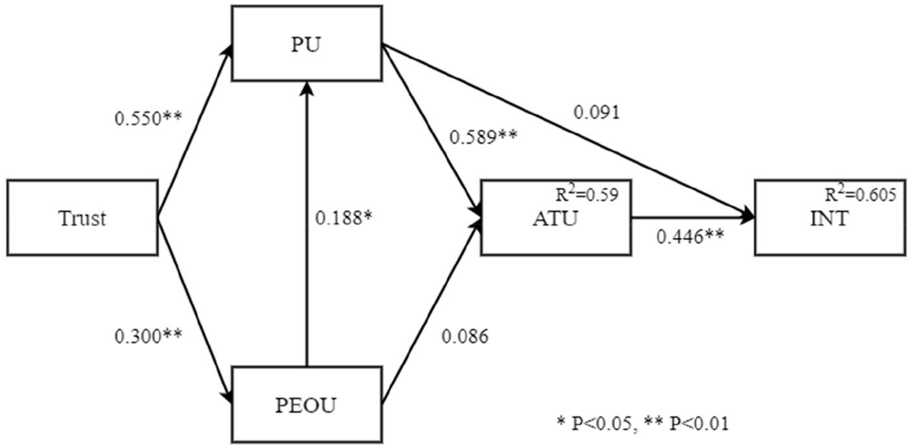

FIGURE 1 | The path analysis of research model (*N* = 136).

DISCUSSION

The results of this study found that the trust relationship between patients and physicians affects patients' understanding of RSS information and their decision-making regarding the procedure (35). Patients' trust in their physicians is regarded as a core factor in the relationship, allowing patients to better understand RSS and its treatment efficacy. In addition, PEOU is found to positively affect PU, which is consistent with the previous results, suggesting that patients who can easily obtain and clearly understand RSS information will feel confidence in determining its potential benefit to themselves. Unlike in previous studies, PEOU is found to not directly affect attitudes toward RSS usage. This study finds that PEOU is affected by PU. Since the definition of PU in this study was modified from Davis (1989), the expression was slightly adjusted but the meaning is consistent following modification and expert validation. The original definition refers to the information technology system used by the user himself or herself, where systems which are easy to operate will result in increased user acceptance. However, in this case, the RSS is operated by a physician. Therefore, this study revised the definition of perceptual ease of use based on the recommendations of experts in the relevant field to obtain a better measurement and interpretation of this dimension (22, 25).

In addition, the results show that, even if patients can easily obtain RSS-related information and understand its purpose, there is no positive correlation with patients' attitudes toward using RSS. PU does not directly affect the willingness to use, but it will indirectly affect the willingness to use through attitude of use. This is the same concept as PU, because RSS is operated by the physician rather than by the patient, where the trust factor provides the patient confidence in the benefits of RSS. However, the results show that the use of RSS to help patients only affects willingness to use indirectly through their attitude (24, 25). That is, in addition to providing patients with relief from their symptoms, willingness to use RSS depends on the patient having a positive attitude toward the technology and confidence that RSS is the correct choice for their condition.

To sum up, use of RSS has increased significantly in recent years and provides advantages over traditional surgery or endoscopic surgery for complicated procedures in difficult surgical sites. Since the introduction of Da Vinci robotic surgery system in Taiwan in 2004, at least 30,000 operations have been completed, and with 80% conducted in the past three years. The present research results indicate that RSS is predominantly used by middle-aged and elderly people, but application is limited by financial considerations as RSS is only covered by Taiwan's social insurance scheme for the treatment of prostate cancer. Given the treatment advantages provided by RSS, the government should consider expanding social insurance coverage to include RSS treatment for more complex lower rectal cancer, or pre-liver transplantation surgery. Continuing advances in medical technology and the prevalence of minimally invasive surgery also provide patients and doctors with additional options for suitable surgical approaches. Therefore, hospitals should seek to implement shared medical decision-making, reducing information asymmetry for patients and empowering them to actively participate in the surgical decision-making process (10, 19).

This research makes two distinct contributions. This study uses TAM to assess the behavior and intention of RSS patients, unlike other studies which primarily focus on the effectiveness of Da Vinci robotic surgery system. This research also proposes that trust will affect patients' personal beliefs in terms of their perception of the surgery as being helpful, or the availability of information about the surgery to make informed decisions. At the same time, this research also helps to explore factors affecting patient willingness to adopt advanced surgical techniques (25, 29).

In terms of practical contributions, this study is mainly based on behavioral intention, and finds that most patients have a certain degree of understanding of RSS, but their most important consideration in determining their willingness to undergo RSS is the effectiveness of the procedure. Therefore, clinicians should seek to clearly explain the benefits of RSS for the specific condition of each patient. Patients' trust in their doctors determines their willingness to accept doctors' suggestions, which in turn will affect the patients' views on the relevant medical information available to them, which serves as the foundation for further decision making. Therefore, doctors serve a key role in communicating critical medical information, and must seek to empathize with their patients, thereby preserving trust and maintaining treatment effectiveness (29, 35).

The TAM was used to measure new technologies in their use and adoption. The literature indicates that modifying the model was primarily adding or removing variables and, in some cases, adding moderators or mediators. The model has limits identified in the literature as the problem of reliably quantifying behavior in an observed survey. In addition, there are notable criticisms identified in the literature, such as the failure of the TAM to notice other issues, such as costs and structural imperatives that push users to adopt an innovation. The TAM will continue to be accepted and modified based on the successful implementation of any new health care technology. This exploratory cross-sectional study does not account for differences between various medical specialties, which should be addressed in future research designs that can also compare the selection factors and intentions of patients who have and have not previously used RSS, thus providing more representative results.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Kaohsiung Medical University. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

H-YK and YW: supervision of the project, design of the research, organization of experiment conduction, data analysis and interpretation, writing, and revision of the article. Y-HH and Y-CY: organization of experiment conduction, data analysis and interpretation, and writing of the article. All authors contributed to the article and approved the submitted version.

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Medical Device Product Innovation Choices in Asia: An Empirical Analysis Based on Product Space

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Due to the increasing demand for health care, identifying and evaluating the feasibility of local medical device innovation and production is an important guarantee for the long-term sustainable development of a national health system, especially for Asian countries/regions that are plagued by aging populations. This article analyzes the international trade data of 46 HS 6-digit medical device products exported from 49 countries from 1999 to 2019, and constructs a global medical device product space. Furthermore, the innovation potential and opportunities of potential medical device products in major Asian countries are evaluated by examining the dynamic relationship between the product distance and the acquisition of comparative advantages for medical device products based on an empirical model. The regression results suggest that a close product distance improves the feasibility of developing a new medical device product. The smaller the product distance is, the more likely it is to increase the diversity of the medical device products of a country by maintaining the existing comparative advantages and gaining potential comparative advantages. Furthermore, we follow the conclusions of the empirical model and analyze the product space evolution, and potential product distance and gains of major Asian medical device exporters. These conclusions may help entrepreneurs identify potential development directions and help government policy-makers formulate policies that are in line with national realities.

Keywords: medical device products, product space, innovation, potential products, potential opportunity gains

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INTRODUCTION

The outbreak of the COVID-19 pandemic has become a major global health concern, greatly raising awareness of the importance of health (1). However, knowledge about this novel virus is still limited (2), leading to increasingly complex global health challenges. The Sustainable Development Goal 3 to ensure healthy lives and promote well-being for all at all ages requires safe, effective and appropriate medical devices for prevention, early diagnosis, and effective treatment of disease [(3), p. 6]. The importance of health technology, especially medical devices, cannot be overstated.

With the ongoing impact of the COVID-19 pandemic on global markets, supply chain disruptions have led to shortages of critical medical devices worldwide. The sudden surge in demand for some medical devices, such as ventilators, has forced many countries to reduce import controls to address the urgent needs of patients and health care systems. It is generally believed that factors such as global population aging, increased life expectancy, the threat of chronic diseases, and the emergence of new technologies in the market have promoted awareness of the importance of obtaining medical devices. There is a growing demand for medical devices for disease diagnosis, treatment, monitoring, and management. This growing global demand for health increases opportunities for national economic development. However, such opportunities are largely concentrated in high-income countries and have minimal impact on low- and middle-income countries [(4), p. 4].

The development of medical devices has historically been concentrated in high-income countries (5) because it is both expensive and risky due to its high complexity (6). Most low- and middle-income countries do not manufacture medical device products themselves but transfer such products from developed to developing countries through low-cost sales or the donation of existing products (technology diffusion) (7). However, it has been reported that ∼40% of medical devices in underresourced areas are unusable (8). This purchasing model has a high risk of technical failure. Therefore, it is necessary to systematically evaluate the feasibility of producing and manufacturing medical devices in a specific environment and improve medical device development through local production.

To this end, this study considers the Asian region. On the one hand, the Asian region contains some of the most dynamic economies in the world, some of which are already at the forefront of global technological development and have great potential for development in the medical device industry. On the other hand, East and Southeast Asia have the largest elderly population in the world (9) and low birth rates in parts of Asia have reduced future labor availability. The current level of medical device development, and national systems and guarantees cannot fully meet the growing health needs of the population. Medical device innovation may become one of the bottlenecks for the long-term sustainable development of Asian health systems.

This study addresses the above issue by introducing a cutting-edge approach involving complexity economics, while also considering product space, which can determine whether it is possible for a country to develop a specific product (10). It has been shown that the success of a new product depends on how close the new product is in the product space to the products that the country has been able to manufacture and export (10–12). In the product space, cross-country heterogeneity is fully considered. The distance between existing products and potential products in each country reflects the differences in production capacity among countries. This distance not only determines the path and extent of industrial transformation, but also implies an important message, that is, the strategy of companies, markets, and countries to determine the direction of innovation.

To support the subsequent evaluation of innovation potential and opportunities of potential medical device products in major Asian countries, we first consider whether the dynamic relationship between the product space and the acquisition of comparative advantages for medical device products is consistent with existing research. We calculate the product space indices for 46 medical device products exported from 49 countries from 1999 to 2019. Regression results confirm that shorter distances in the medical device product space have a positive impact on the acquisition of comparative advantage. Through correlation decomposition, it is found that shorter product distances promote industrial upgrading by gaining comparative advantage and preventing products from losing the advantage. On this basis, we extend the empirical conclusions, identify the evolution patterns of medical device product space in China, Japan, Singapore, Malaysia, and South Korea, and evaluate the options for potential product innovation in the above countries. It may provide guidance for corporate decision-makers and policy-makers in terms of medical device product support and industrial structure adjustment.

The remainder of the article is structured as follows: Section Theoretical Basis and Hypotheses outlines the theoretical background and presents the hypotheses. Section Data Sources and Research Methods describes the variables and regression models. Section Empirical Results presents regression analysis. Section Product Space Analysis of Medical Devices in Asia discusses medical device product innovation choices in Asia. Section Conclusions and Directions for Further Research presents the conclusions, limitations, and directions for further research.

THEORETICAL BASIS AND HYPOTHESES

Research on Medical Device Products and Innovations

A medical device is defined as an article, instrument, device or machine used to prevent, diagnose or treat disease, or to detect, measure, restore, correct or modify the structure or function of the body for a health purpose. Its primary mode of action is not based on pharmacological, metabolic or immune processes (13). Medical devices defined in this way are numerous and contain a very diverse set of technologies (14). Innovation is a complex interaction in a technical knowledge base to generate new and nondeterministic processes (15). Reasonable allocation of technical knowledge resources within an organization and timely adjustment of the structure are very important (16). It should be noted that there are multiple definitions of innovation related to medical devices (17). The medical device innovation discussed in this study continues the concept of Schumpeterian innovation, that is, new products start out as inventions and turn into innovations as they are commercialized (18).

As mentioned in the Introduction, the main source of medical device innovation remains limited to high-income countries. As the world's largest medical device market (19), the United States is constrained by limited availability of venture capital and slow commercial rates, etc., resulting in "industry outflow" (20). This also means that many medical device products exported by developing countries may also be manufactured for high-income countries. Compared to innovations from the technological frontier in high-income countries, developing countries are in a relatively resource-scarce environment. This resource-constrained business model and innovation, namely frugal innovation, has received extensive attention from academia (21, 22).

Medical device innovation and its economic evaluation involve many complex factors (14) and stakeholders (20). Stringent regulations make medical device design more complex, and successful medical device innovations often go beyond the functionality of the product itself (23). Kirisits and Redekop (14) suggested that the economic evaluation of medical devices should consider both external factors (regulatory framework, industry structure, short life cycle, and early market diffusion) and device-level factors (design constraints, program integration, repeatability, dynamic efficiency, and resource usage). Medical device product innovation requires a complex assessment of the possibility of industrialization of a new local medical device product. This innovation requires not only the development of technology but also a systematic assessment, including needs, the usage environment and market factors [(4), pp. 18–19], to promote the effective development and use of technology. Therefore, researchers encourage the use of systematic viewpoints to make comprehensive evaluations (22, 24, 25) and pay extensive attention to the medical device background by researching in the elements of medical device innovation.

Medical Device Product Space

In terms of medical technology, innovation can be divided into the most common evolutionary innovation and the rare revolutionary innovation (26). Evolutionary innovation is the cumulative learning or experience gained through the use of the technology. Gelijns and Rosenberg (27) compared the dynamic interaction view of technological change with the linear model of medical innovation and found that one of the characteristics of medical device innovation is path dependence. The rare revolutionary innovation may come from technology diffusion across disciplines. In other words, medical device innovation is a dynamic and complex process. From idea to invention, to development, and to the commercialization of medical device products, the evolutionary innovations are finally expressed as marketable products.

Product space theory argues that industrial upgrading is not continuous, and its space evolution is formed by technological, organizational and institutional capabilities accumulated at the local level (28). Foreign trade data can be assessed as outcome indicators arising from the impact of a number of market-related parameters. This means that successful innovation will be reflected in the acquisition of comparative advantages by export products. The generation of comparative advantages requires not only the support of technology, but also the support of manpower, material, knowledge, policies and systems. It can be considered that the product space is in line with the suggestion for medical device innovation that the possibility of industrialization of a new local medical device product should be evaluated from a systematic perspective.

Hidalgo and Hausmann (29) investigated the evolution of a country's comparative advantage based on the product space, and found that product distance has an important impact on the evolution of a national or regional industry. Technology-related products have similar requirements for various production factors, production technology, and management experience. Whether a country can realize the transfer of product comparative advantage depends not only on the current capacity endowment and the similarity between the capacity endowment required for the production of new products and that for existing products (similarity of local factors), but also on the government's guidance for industrial capacity endowment (30). The more similar the capacity endowment required to produce a new product is to that accumulated by the existing product, the closer the two products are in the product space. This has been supported in studies of specific industries, such as the biotechnology industry (31), the European nanotechnology industry (32), and the green industry (11). In summary, the successful development of a new product is more likely to occur in areas with an existing product with a similar knowledge (technical) base. Hence, the following hypothesis is proposed:

H1: In the medical device product space, a close distance improves the feasibility of new product development.

If many countries have comparative advantages in two particular products, it indicates that the two products require similar capabilities and can be regarded as related products (10). The deepening of the correlation between products and the derived diversity are the fundamental driving forces which stimulate national industrial upgrading. Specifically, the factor endowment structure determines the industry distribution and development direction. Combined with the characteristics of medical device product innovation, the factor endowment of regional production has two main mechanisms for the evolution of comparative advantage: For products with comparative advantages, accumulating experience and deepening the relationship between products based on existing technologies will enhance the comparative advantage. For products that do not have comparative advantages, the closer they are to products with comparative advantages, the greater the relationship between them, and the greater the opportunity to stimulate product derivative innovations. In summary, related product innovation can be regarded as a recombination of existing capabilities. Continuous recombination not only consolidates the position of advantage products but also expands new and diverse derivative products. Hence, the following hypothesis is proposed:

H2: In the medical device product space, a close product distance helps maintain the existing comparative advantages and promotes product innovation by gaining potential comparative advantages to enhance the diversity of medical device products of a country.

DATA SOURCES AND RESEARCH METHODS

Product Space Approach

The specialization matrix organizes the location information of the economic activities in which the country has comparative advantages in the form of a matrix (33), and indicates whether a country has a comparative advantage in product production through revealed comparative advantage (*RCA*). X_{cp} is the total exports of product P from country C. The revealed comparative advantage of product P of country C is expressed as:

$$RCA_{cp} = \frac{\frac{X_{cp}}{\sum_c X_{cp}}}{\frac{\sum_p X_{cp}}{\sum_c \sum_p X_{cp}}}$$

When dealing with the specialization matrix, the product space approach often further defines it as a binary specialization matrix. Hidalgo and Hausmann (29) suggested using $RCA_{cp} \geq 1$ as the threshold of national product specialization. The binary specialization matrix M_{cp} is expressed as follows:

$$M_{cp} = \begin{cases} 1 & RCA_{cp} \geq 1 \\ 0 & otherwise \end{cases}$$

The row sum of M_{cp} describes the diversity of export products of a country (*Diversity*), which measures how many different types of products a country produces. It is defined as follows:

$$k_{c,0} = \sum_p M_{cp}$$

The column sum of M_{cp} describes the ubiquity of export products (*Ubiquity*), which measures the number of countries producing a certain product. It is defined as follows:

$$k_{p,0} = \sum_c M_{cp}$$

On the basis of the specialization matrix, Hidalgo et al. (10) defined a $p \times p$ product proximity (*Proximity*) matrix, $\Phi_{pp'}$, that is, there is a globally defined proximity between every two products to represent the distance between them in a certain period. They suggested that there is a high proximity between two products requiring similar production capacity. $\Phi_{pp'}$ is measured by the possibility of joint export. The greater the probability that a country exporting product p also exports product p', the closer the two products are.

$$\Phi_{pp'} = \frac{\sum_c M_{cp} M_{cp'}}{\max(k_{p,0}, k_{p',0})}$$

Moreover, this globally defined matrix is widely expressed as a product space network map using a visual network. This expression visually simulates the evolution of a country's production structure and allows easy mapping of the productive capacity of that country. The construction method and information identification will be discussed in detail in Section Product Space Evolution.

The knowledge capacity of each country to produce a product is different. Therefore, it is necessary to measure the distance between the product and the existing production structure of the country. The product proximity $\Phi_{pp'}$ is fixed on a global scale. The distance matrix (*Distance*) can be defined as the distance of a product being the sum of the proximities of the given product to all other products that are not currently exported at that location:

$$D_{cp} = \frac{\sum_{p'} (1 - M_{cp'}) \Phi_{p,p'}}{\sum_{p'} \Phi_{pp'}}$$

Finally, on the basis of the above product space indices, we further analyze the potential development index of the national industry. In other words, if industrial upgrading follows the evolution of comparative advantages, we will examine the potential of products that do not have comparative advantages in the country in the current period.

We define the potential distance PD_{cp}, which is calculated as the dot product of the distance matrix D_{cp} and the binary specialization matrix M_{cp}, and define the distance of the advantage product as 0, thus clearly showing the proximity of the country's current nonadvantage product to the advantage product.

Second, we define the potential product gain matrix POG_{cp}, which is calculated as the dot product of the opportunity gain matrix OG_{cp} and the binary specialization matrix M_{cp}. Opportunity gains (*OG*) measure the gains to a country for opening up future diversification opportunities from developing a particular product. The increase in opportunity gains explains the complexity and distance of a product that is not produced in a country or how close the new product is to existing functionality. It is defined by Hausmann et al. [(34), p. 54] as:

$$OG_{cp} = \sum_{p'} \frac{\Phi_{p,p'}}{\sum_{p''} \Phi_{p'',p'}} (1 - M_{cp'}) PCI_{p'}$$

The product complexity index (*PCI*), i.e., the quantity and complexity of the know-how required to produce a product, is calculated according to Hidalgo and Hausmann (29).

We first construct the matrix $\tilde{M}^P_{p,p'}$:

$$\tilde{M}^P_{p,p'} \equiv \sum_c \frac{M_{cp} M_{cp'}}{k_{c,0} k_{p,0}}$$

Next, we find the matrix eigenvalue $\vec{q}$ and the corresponding eigenvector $\vec{Q}$, extract the eigenvector $\vec{Q}_{l2}$ corresponding to the second largest eigenvalue λ_{l2}, and obtain the *PCI* calculation formula:

$$PCI_{cp} = \frac{\vec{Q}_{l2} - average(\vec{Q})}{stdev(\vec{Q})}$$

Variables and Models

To test the hypotheses to support further analysis, we use the econometric model implemented by Hausmann and Klinger (28) to investigate the product space, which in this case is the dynamic relationship between the product distance and the acquisition of comparative advantages. It is expressed by Equation (1):

$$y_{c,p,t} = \beta_0 + \beta_1 y_{c,p,t-1} + \beta_2 Distance_{c,p,t-1} + \beta_3 X + \varepsilon \quad (1)$$

where the explained variable $y_{c,p,t}$ is the comparative advantage of product p of country c in year t, which is represented by the binary specialization matrix $M_{cp,t}$ in year t; the explanatory variable $y_{c,p,t-1}$ is the comparative advantage $M_{cp,t-1}$ of product p of country c in the previous period; $Distance_{c,p,t-1}$ is the distance between product p in country c and the product with comparative advantage in that country in the previous period, which is represented by the distance matrix D_{cp}; X is the vector of country-time and product-time dummy variables to control for changes in country or product characteristics over time; and ε is the perturbation term.

To further separate product upgrading and loss of advantage (28), we include an interaction with product distance to examine the effect of product distance on the gain or loss of comparative advantage. Thus, Model (2) is developed to test Hypothesis 2:

$$y_{c,p,t} = \beta_0 + \beta_1 y_{c,p,t-1} + \beta_2 y_{c,p,t-1} * Distance_{c,p,t-1} + \beta_2 (1 - y_{c,p,t-1}) * Distance_{c,p,t-1} + \beta_3 X + \varepsilon \quad (2)$$

If product p in country c does not have a comparative advantage in period $t-1$, the product distance will affect product upgrading in period t through β_2, and this index indicates the role of product distance in product upgrading. If product p in country c already has a comparative advantage in period $t-1$, the product distance will affect the comparative advantage of the product in period t through β_1, and this index indicates the role of product distance in preventing the product from losing its comparative advantage.

Descriptive Statistics of Sample Data

A total of 46 medical devices products (**Appendix 2**) were identified by matching the 56 HS 6-digit medical device products provided by Yilmaz and Bayrak (35) with the HS 6-digit products in the global bilateral trade from 1995 to 2019 in the CEPII-BACI database.

The data of these medical device products were further processed. First, the exports of medical device products from each country/region in the world in 2019 were sorted in descending order to identify a total of 49 countries/regions whose total exports accounted for 99% of the world's total (**Appendix 1**). Second, the time series of the above countries/regions from 1995 to 2019 were examined, revealing that the export data of Belgium from 1995 to 1998 were missing. Therefore, this study covers a period of 20 years from 1999 to 2019 by reducing the sample time series. To reduce the influence of temporary factor changes on the sample, we grouped the data every 5 years to obtain 4 periods of data according to Hausmann and Klinger (28).[1] Descriptive statistics of each variable in the product space are shown in **Table 1**.

[1]We tested the optimal lag order of the model before the empirical test. The BIC and HQIC information criteria indicated an optimal lag order of 4 and 5, respectively, which was basically consistent with the five-year panel study by Hausmann and Klinger (28).

EMPIRICAL RESULTS

Table 2 reports the regression results of Model (1), Model (2), and the robustness test.

In Model (1), the regression coefficient of the distance between medical device products in the previous period is significantly negative at the 1% level. Each 1% increase in the distance decreases the probability of developing innovative products by 96.6%. As discussed in Hypothesis 1, increased product distance reduces the likelihood of new product development, so medical device product innovation choices are less likely to be jump-started. Considering that the explained variable is a binary dummy variable, we use RCA to replace M for the robustness test. *L5.DISTANCE* is significantly negative at the 10% level, indicating that our regression results do not depend on the definition of the explained variable.

Model (2) considers the degree of influence of distance on the export of innovative products and on the abandonment of the export of existing products with comparative advantages. The coefficient of the *L5.M* × *DISTANCE* interaction, which represents the degree of influence of distance on the loss of advantage of a product, is significantly negative at the 1% level. This interaction indicates that the greater the product distance is, the more likely the products with existing comparative advantages will lose their advantages and vice versa. The coefficient of L5.M_d × *DISTANCE* interaction, which represents the degree of influence of distance on the export of innovative products, is significantly negative at the 1% level. This degree of influence indicates that the probability of products gaining comparative advantages decreases as the product distance increases. In other words, products with a closer distance are more likely to be upgraded.

The above conclusions are basically consistent with those of previous empirical research on product space and comparative advantage (28).

We further consider the heterogeneity of medical device product innovation across countries with different income levels as mentioned in the Introduction. The sample countries/regions are divided into 31 high-income, 11 upper middle-income, and 7 lower middle-income countries/regions based on the 2020 World Bank national income classification. From the perspective of sample size, the number of high-income countries/regions is more than twice that of upper middle-income countries/regions and lower middle-income countries/regions. This number is in line with the notion that the medical device industry is concentrated in high-income areas.

As shown in **Table 3**, the estimated coefficients of the explanatory variable *M* are all significantly positive at the 1% level, with no significant difference across income levels. The estimated coefficients of the explanatory variable *DISTANCE* are significantly negative at 5%, which generally conforms to the hypothesis. The estimated absolute value first increases and then decreases with the decrease of the national income level. The effect of distance on medical device product innovation in upper middle-income countries is far greater than that in lower middle-income countries.

TABLE 1 | Descriptive statistics of each variable.

Variable	Description	Obs	Mean	Std. Dev.	Min	Max
RCA	Comparative advantage	47,334	1.273229	3.798106	0	110.5997
M	Binary comparative advantage	47,334	0.2776017	0.4478205	0	1
DISTANCE	Product distance	47,334	0.7139533	0.1323965	0.2463988	0.995772
OG	Potential opportunity gains	47,334	−0.0224291	0.2386412	−1.754847	1.597928
PCI	Product complexity	47,334	0.0641917	0.9090287	−2.230307	2.992397
PROMIX_MAX	Maximum proximity	47,334	0.4036323	0.254947	−0.1532028	1.155142
PROMIX_AVE	Average proximity	47,334	0.0910649	0.1921174	−0.4266038	0.3655137
NUM_LINK	Number of product links	47,334	43.45135	1.69681	30	45
DIVERSITY0	Country diversification	45,080	12.73061	4.779994	1	26
UBILITY0	Product ubiquity	45,080	13.56087	4.272888	4	26

TABLE 2 | OLS model estimates.

	Model (1) *M*	Model (2) *M*	Robustness test RCA
L5.M	0.529***	0.509***	
	(0.022)	(0.093)	
L5.RCA			0.770***
			(0.043)
L5.DISTANCE	−0.966***		−1.275*
	(0.078)		(0.677)
L5.MxDISTANCE		−0.949***	
		(0.117)	
L5.M_dxDISTANCE		−0.980***	
		(0.089)	
HS6+YEAR_FE	YES	YES	YES
COUNTRY+YEAR_FE	YES	YES	YES
N	36,064	36,064	36,064
R^2	0.4779921	0.4780005	0.7077702
F	1104.814	970.275	715.2861

*$p < 0.1$, ***$p < 0.01$.

Finally, we tested heterogeneity by region. The sample countries/regions are divided into 1 in Africa, 6 in America, 16 in Asia, 24 in Europe, and 2 in the Pacific region based on the United Nations Statistics Division (USUD) classification. Given that the sample size of Africa and the Pacific region is not large enough to run the fixed-effects model, we only report the regression results for America, Asia, and Europe (**Table 4**). The regression results show that the regression coefficients of *L4.DISTANCE* in the three regions are all significantly negative at the 1% level. Among them, medical device product innovation in Asia is most affected by product distance, losing 1.051 units of innovation opportunities for every additional unit of distance. America is relatively less affected by product distance, losing 0.883 units of innovation opportunities for every additional unit of distance. Compared with America, medical device innovation in Asia is more inclined to promote product diversification by selecting products with similar attributes. We will discuss the evolution path and product innovation choices of the medical device industry in major Asian countries in detail in Section Product Space Analysis of Medical Devices in Asia.

PRODUCT SPACE ANALYSIS OF MEDICAL DEVICES IN ASIA

As discussed above, Asia is one of the most dynamic markets for the development of the medical device industry. In the empirical analysis, the regression coefficient of product distance for Asia suggests the product innovation path in Asia. To explore the network characteristics of medical device product innovation in Asia, we construct a product space evolution diagram for medical device exports from major Asian countries. The map is based on the global medical device product space. Based on the sample processing in Sections Data Sources and Research Methods and Empirical Results, we also construct the product space network map of 1999, 2004, 2009, 2014, and 2019 with an interval of 5 years, and mark the products with obvious comparative advantages in each country on the nodes for analysis.

This article follows the product space network strategy of Hidalgo et al. (10). First, we calculate the maximum spanning tree of the average medical device product proximity matrix, establish 46 product nodes and 45 links of the product proximity network, and maximize the total proximity of the network. Second, we add further links, and select an appropriate proximity threshold to make the average degree of the network equal to 4. This is a known common rule for effective network visualization (33). Here, we choose to include all adjacent links ≥0.4 to form a network consisting of 46 nodes and 92 links. Third and finally, for better visualization, we use the ForceAtlas2 algorithm in Gephi to optimize the network view, add attributes to the size and color of the nodes, and adjust the layout to obtain a medical device product space map (**Figure 1**).

Product Space Evolution

Figure 2 shows the evolution of the complexity of medical device products from 1999 to 2019. The color of the label represents the PCI. The gradual change from green to red represents changes from low to high product complexity. Overall, the green nodes gradually spread to the edge over time, which means that the product complexity decreases along the dense area to the edge. Over time, an increasing number of countries have possessed the necessary factors of medical device products in the dense area. Among the two branches, the product complexity of the

TABLE 3 | Model estimates of the effect of product distance on comparative advantage by income level.

Income level	(1) Basic Reg	(2) High income	(3) Upper middle income	(4) Lower middle income
L5.M	0.529***	0.544***	0.505***	0.522***
	(0.022)	(0.027)	(0.047)	(0.042)
L5.DISTANCE	−0.966***	−0.908***	−1.140***	−0.602**
	(0.078)	(0.090)	(0.204)	(0.178)
HS6+YEAR_FE	YES	YES	YES	YES
COUNTRY+YEAR_FE	YES	YES	YES	YES
N	36,064	22,816	8,096	5,152
R^2	0.4779921	0.494581	0.516447	0.4913027
F	1,104.814	1,162.517	113.1427	94.81124

$^{**}p < 0.05$, $^{***}p < 0.01$.

TABLE 4 | Model estimates of the effect of product distance on comparative advantage by region.

Region	(1) Basic Reg	(2) America	(3) Asia	(4) Europe
L5.M	0.529***	0.583***	0.498***	0.519***
	(0.022)	(0.040)	(0.047)	(0.030)
L5.DISTANCE	−0.966***	−0.883***	−1.051***	−1.009***
	(0.078)	(0.183)	(0.208)	(0.100)
HS6+YEAR_FE	YES	YES	YES	YES
COUNTRY+YEAR_FE	YES	YES	YES	YES
N	36,064	4,416	11,776	17,664
R^2	0.4779921	0.6279242	0.4707612	0.4886709
F	1104.814	1322.659	138.2341	1271.65

$^{***}p < 0.01$.

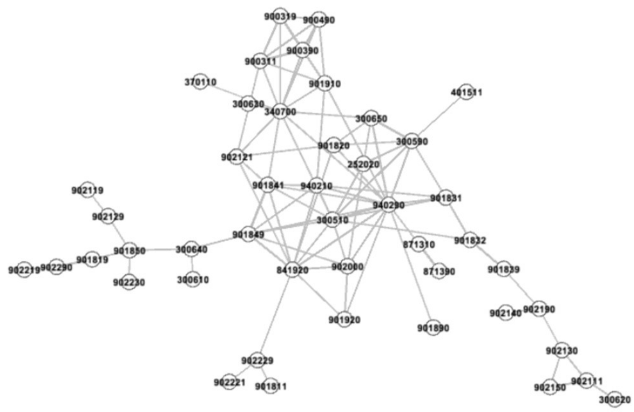

FIGURE 1 | Medical device product space.

left branch decreases year by year, and the right branch remains highly complex.

We select the top five countries[2] in Asia in terms of export value in 2019 as representative examples to analyze the dynamic evolution of product space in Asia. In the product space map, the node size represents the total world exports of the product in that year; black nodes represent products with obvious comparative advantages in representative Asian countries in each period; and gray nodes represent other products that do not have obvious comparative advantages (**Figures 3–7**).

In general, the product space maps of major medical device exporting countries in Asia have the following characteristics: (1) the number of medical device products with comparative advantages in the country is increasing year by year; (2) innovative medical device products tend to be created near existing products along the links; and (3) products with comparative advantages tend to cluster from the edge to the dense area.

As shown in **Figures 2**, **3**, China exports a wide variety of medical device products with a low technical level. Its product space evolution has obvious overall characteristics. New products are mainly concentrated in the densely connected area, with significant growth from the edge to the center. However, this trend is similar to the evolution of PCI. Most medical device products with comparative advantages in China are still of low complexity.

As shown in **Figure 4**, Japan had the ability to produce complex products in the early evolution of medical device products (left branch). It evolved from the edge to the center along the product links, following the product space law. By also considering the evolution of PCI, it is found that Japan is gradually losing its advantage in complex products. The total number of medical device products with comparative advantages in Japan did not change from 2014 to 2019. The obvious feature is that Japan lost the comparative advantage of the largest node (HS 901890) in the product space map, but it gained a new comparative advantage in the complex product area in the lower right corner (HS 902190).

[2]The top five countries in terms of medical device exports in Asia in 2019 are China (41%), Japan (14%), Singapore (12%), Malaysia (7%), and South Korea (6%).

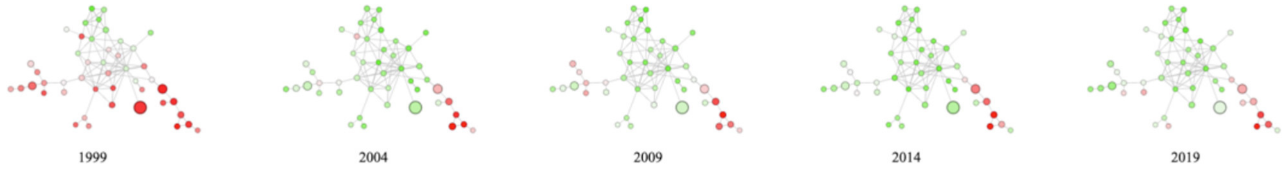

FIGURE 2 | Evolution of medical device product complexity from 1999 to 2019.

FIGURE 3 | Evolution of medical device product space in China.

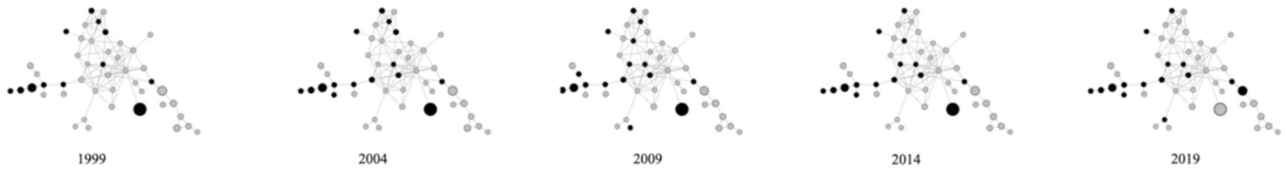

FIGURE 4 | Evolution of medical device product space in Japan.

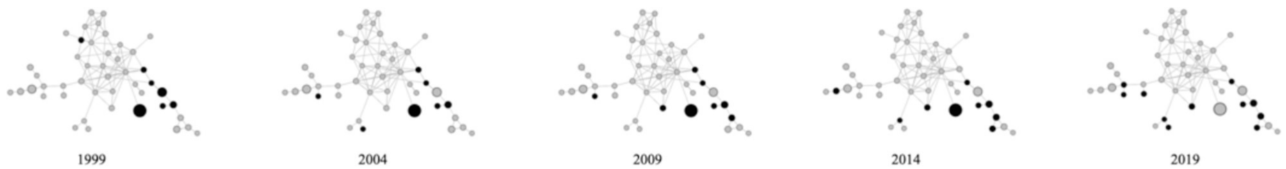

FIGURE 5 | Evolution of medical device product space in Singapore.

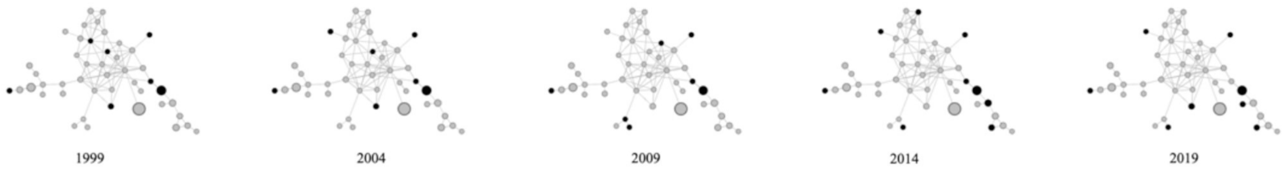

FIGURE 6 | Evolution of medical device product space in Malaysia.

The total number of medical device products with comparative advantages in exports is not large for Singapore. It mainly produces and exports highly complex medical device products. **Figures 2**, **5** show that Singapore exported highly complex products in its early evolution, similar to Japan. From the perspective of product space, the two counties occupied the left and right complex areas, forming their own distinct but nonconflicting advantages. As the evolution progressed, Singapore not only always had the knowledge of complex products to maintain its advantage (right branch), but also made correct judgments about the frontier of product innovation to gain comparative advantages (HS 902230, HS 300610, and HS 901811).

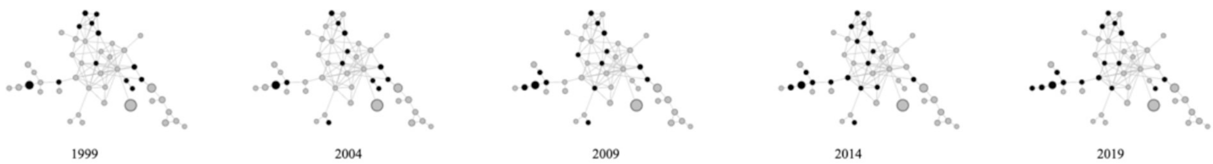

FIGURE 7 | Evolution of medical device product space in South Korea.

Malaysia is the country with the lowest number of medical device products with comparative advantages and the fewest changes among the representative countries in Asia. The characteristic of Malaysia's product space evolution is that it always had a comparative advantage in some complex products (right branch) and successfully gained a comparative advantage in derivative products after 2014. However, other advantage products were always located at the edges of the product space and did not develop product diversity along the links.

Korea had relatively scattered products with comparative advantage in the initial stage, with an overall evolution trend of increasing advantage products from the edge to the dense area. Its evolution path in the left branch is similar to that of Japan. However, as shown in the product space map in 2019, South Korea lost some of its advantage products in the dense area (HS 340700 and HS 901820) and did not achieve breakthroughs in complex products.

The above facts suggest that (1) the evolution of medical device product space in Asian countries mostly has the characteristic of evolving along the maximum proximity between products; (2) there are obvious differences in the innovation strategies of medical device products between countries with different resource endowments; and (3) the reduction of product complexity is accompanied by technology diffusion, and more countries will have the opportunity to gain comparative advantages, while countries that have core knowledge may lose the advantage.

Potential Product Distance Matrix Analysis

The potential distance matrix of medical device products is a matrix composed of countries and medical device products. Due to space limitations, this article only discusses the potential product distance matrix of Asian countries/regions in 2019 as an example. The rows of the matrix are arranged from left to right in descending order of product complexity in that year. The cells are filled with potential product distances. As the distance increases, the color changes from green to red, as shown in **Figure 8**.

The potential product distance matrix provides the following information: (1) products currently produced by each country/region that already have a comparative advantage (dark green); (2) potential products that are likely to be produced by each country/region (light color); and (3) products that are highly unlikely to be produced by each country (dark red).

The data show that Saudi Arabia, China, and Hong Kong, China are the top three countries/regions in Asia in terms of product diversity with 24, 23, and 18 export products, respectively. They have a small overlap in high-complexity products and a large overlap in low-complexity ones. In terms of the number of light-colored cells, Saudi Arabia is the most capable country in Asia to produce diversified medical device products (38 products), followed by China (27) and Hong Kong, China (21). A dark-colored cell means that the country does not have the capacity to produce the product, so it is highly unlikely to be produced by that country. Pakistan, Malaysia, Indonesia, and Vietnam will still be at a disadvantage in the medical device industry in the future.

Potential Product Gains

We continue to analyze the potential product gains for these representative countries with China, Japan, Singapore, Malaysia, and South Korea as examples. The product space evolution analysis reveals the shortcomings and suggestions for of the current medical device industry of each country to a certain extent, such as how China can overcome the lack of high-complexity products, whether Malaysia should seek product diversity, how Japan and South Korea can recover the advantage in complexity, how Singapore continues to identify high-complexity products and how India prevented the loss of comparative advantage. This section will create distance-opportunity gain graphs for potential medical device products (**Figure 9**) and provide suggestions for these countries to further pursue new opportunities for product innovation.

The distance-opportunity gain graph for China is consistent with its evolution of product space. It can be seen that opportunity gains are negative for most products in China. The negative sign comes from PCI. This measurement means that the gains of these products are below average. China can consider two steps in its pursuit of high-tech products: First, it can continue to upgrade along the shortest product distance along the original path in the short term. These products are still of low complexity and provide no significant potential opportunity gains but are relatively easy to implement. Examples are HS 252020, HS 901820, HS 901841, HS 901849, and HS 902000. Second, it should explore products that have both positive gains and the shortest distance in the medium and long term, such as HS 901832 and HS 901839.

Japan and South Korea can choose to seek short-term breakthroughs along the shortest path. An example is HS 902121. On the other hand, due to their relatively rich technical knowledge base of medical device products, their reachability distance for seeking high-tech products is relatively short. In other words, it is easier for them to realize the jump to complex

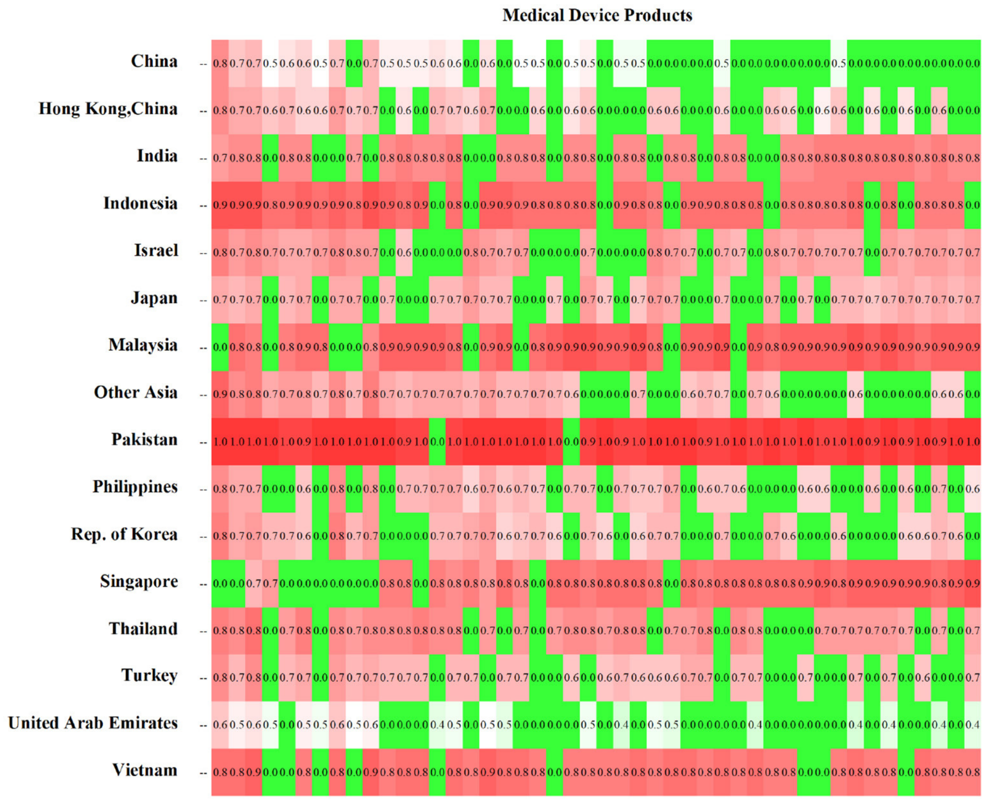

FIGURE 8 | Potential product distance matrix by country/region.

products. Hence, the key is to identify high-potential products. Therefore, we suggest that the two countries prioritize the development of high-gain products at an appropriate distance. For example, Japan can consider HS 902130, which is at an appropriate distance of 0.677 and has the second highest complexity, HS 901890, which is at a shorter distance and still provides above-average gains, and HS 902190, which is at a slightly farther distance and has the fifth highest complexity. For Korea, the product we identify is HS 300610, which can reach the highest-complexity product in the shortest distance (ranked 7th in complexity in 2019) and provides above-average potential opportunity gains.

Singapore is the country in Asia that has the production capacity for complex products. As shown in the opportunity gain graph, HS 902111, which is at a distance of 0.6826 and ranked third in complexity, and HS 901839, which is at a distance of 0.744 and ranked fourth in complexity, are relatively discrete, are at a short potential distance, and provide high potential opportunity gains. The other products appear to be concentrated at a longer distance and provide smaller opportunity gains; in other words, they are in an area that is unlikely to be developed in the future.

In the product space evolution map, we found that Malaysia has mastered some high-tech products. However, there is a lack of product diversity, which is explained by the potential distance-gain graph. We found that all medical device products are at a distance of >0.7 in Malaysia, which is very unfavorable for product derivative innovations. From the perspective of opportunity gains, HS 902230 should be prioritized for breakthrough innovation.

CONCLUSIONS AND DIRECTIONS FOR FURTHER RESEARCH

Conclusions and Implications

This article answers the question of how to evaluate the feasibility of medical device innovation and production in a specific environment from the perspective of national output and capability. To evaluate this innovation, we consider the systematic requirements for the innovative development of medical devices and employ the product space approach at the forefront of complexity economics. Furthermore, taking the medical device product space in Asia as an example, we evaluate the innovation potential and opportunities of potential medical device products in representative countries, supplement the analysis of current national policies on medical device products with export advantages and potential export advantages for national policy-makers and stakeholders, and provide guidance for formulating policies in line with national industrial development. The following conclusions are drawn:

First, empirical analysis confirms that a close product distance improves the feasibility of the development of a new medical

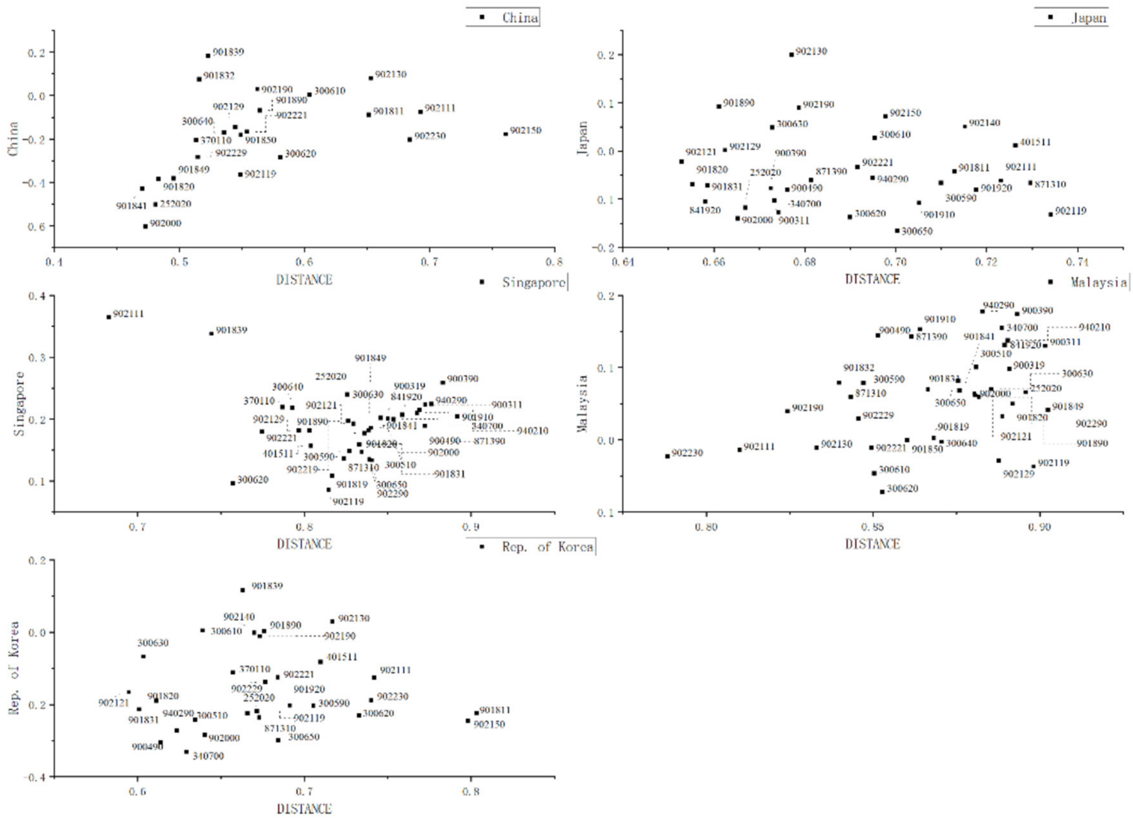

FIGURE 9 | Distance-opportunity gain graphs for potential medical device products.

device. Further analysis by separating comparative advantages suggests that a close product distance helps maintain the existing comparative advantages and promotes product innovation by gaining potential comparative advantages to enhance the diversity of medical device products in a country.

Second, the product space evolution map of medical devices in Asia reveals that medical device product innovation and industrial evolution in major Asian countries mostly evolve along the minimum product distance but show heterogeneity in the selection of evolution paths. By also considering the evolution of product complexity, it is found that the reduction of product complexity is accompanied by technology diffusion, and more countries will have the opportunity to gain comparative advantages. For example, the diversity of low-complexity products is a specific characteristic of China.

Third, the potential product distance matrix visualizes the diversity of medical device exports in Asia. Among Saudi Arabia, China, and Hong Kong, China has the most diverse medical device products, while Pakistan, Malaysia, Indonesia, and Vietnam lack diversity. The potential product gain analysis provides-policymakers and stakeholders with a perspective focused on medical device innovation. We recommend prioritizing the development of high-gain products at the shortest distance. For example, for China, although there is a wide variety of medical device products, they are concentrated in low-complexity areas. Based on the shortest distance and the greatest potential gain, we identify the complex product HS 901832 (Medical, surgical instruments and appliances; tubular metal needles and needles for sutures) with the greatest potential for breakthroughs.

These conclusions can help countries identify the necessary capabilities that they already have for the development of medical device products and determine next steps. The conclusions are not limited to Asia but can be extended to all regions where statistics are available.

Limitations and Directions for Further Research

This study has two limitations. The first lies in the scope of medical device products. There is no uniform classification for medical device products, and fewer products are eventually included in trade studies. Therefore, our conclusions depend to a certain extent on the product list we selected. In the future, we will continue to focus on the list of medical device products in this field of research. The second limitation is the partial product space. We only considered a list of 46 manufactured medical device products. This product space may ignore the impact of other related industries on the medical device industry. In the future, we will build a complete product space on the basis of improving the list of medical device products and comprehensively consider the impact of related industries.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

All authors undertook research, writing, and review tasks throughout this study and have read and agreed to the published version of the manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpubh.2022.871575/full#supplementary-material

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ORIGINAL RESEARCH
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Exploring the Relationship Between Hospital Service Quality, Patient Trust, and Loyalty From a Service Encounter Perspective in Elderly With Chronic Diseases

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Based on the service encounter perspective, this study combines theoretical foundations for such factors as service quality and the characteristics of the hospital service industry to develop a research model scale to investigate whether the quality of hospital services affects patients' perceptions of health service encounters, trust, and loyalty. Nowadays, with the advancement of medical technology, patients pay more attention to the quality of medical services and good service encounters provided by healthcare professionals in order to establish positive patient relationships; hospitals need to improve their own service quality and establish good patient trust relationships so that doctor-patient satisfaction and loyalty can be improved. In a review of related literature, this study found that most past studies focused on issues related of quality of medical services and patient satisfaction, but ignored those related to the relationship between medical service encounters and patient trust and loyalty, as well as the lack of scientific measurement markers for service encounters in the Chinese medical service industry. Therefore, this study uses the Service Encounter Perspective and Service Quality Theory Development Research Scale to collect and analyze data for a typical case of a Chinese tertiary hospital. Finally, this study explores the relationship between the four variables of service quality, service encounter, trust, and loyalty by means of a questionnaire and statistical analysis of the data. Finally, it is concluded that the higher the service quality of the hospital, the higher the customer trust, the higher the service encounter, and in the greater the doctor-patient loyalty.

Keywords: hospital service quality, trust, service encounter, doctor-patient loyalty, SERVQUAL

INTRODUCTION

The original purpose of the medical service industry is to meet the medical needs of the society and to solve the problems of old age and sickness. Currently, medical service providers have adopted a patient-centric business strategy, and it has become a challenge and an important evaluation marker for medical service providers to improve their service encounter and quality to meet the needs of patients and to increase their trust in hospitals (1–3). The report of the 19th National Congress of the Chinese Communist Party clearly states that the quality of medical care should be continuously improved to enhance the health of the people (4). In addition, the Chinese people's concern for the quality and health of hospital services has made the service quality and attitude of medical staff a relevant topic throughout all of society (5). However, due to the influence of the old medical system, China's medical and health system is undergoing profound changes, giving rise to many problems, which has resulted in a gap in the people's demand and expectation for medical services. This is an important factor causing social disharmony and instability.

Therefore, public hospitals are focusing their efforts on medical services, which has practical and theoretical implications for the continuous improvement of service quality and sustainable and healthy development of public hospitals. To reduce the occurrence of medical disputes, public hospitals must improve the quality of services with a focus on "patient safety." The improvement of patients' expectations of the quality of medical services will build long-term trust between doctors and patients and lay the foundation for a good branding of the hospital (6, 7). At the same time, patients' evaluation of hospital services can be used to assess the overall strength of the hospital in terms of service excellence, staff technical standards, and management levels (8). In view of customers' demand for hospital service quality and the total national health insurance budget limit, public hospitals must undergo the following changes to be sustainable: (**i**) improve the quality of services (6, 7); (**ii**) pay attention to patient satisfaction after medical service encounter (1, 9); and (**iii**) improve patient and family satisfaction and loyalty to medical care (10). Among these, medical service encounter is the interaction between frontline healthcare workers and patients, and is also the most important part of service quality to patients. When strengthening competitiveness in hospitals, doctors and nursing staff are the frontline medical staff that face and have direct contact with patients. Therefore, medical service encounter is a key factor in maintaining and strengthening the doctor-patient relationship, thereby creating patient loyalty, and thus is a key factor in the survival of today's hospitals.

Medical service encounters happen when patients need highly professional medical services. In particular, the elderly or chronic disease patients require long-term medical services, including dialysis, Alzheimer's disease prevention, diabetes prevention, and hypertension prevention (6). These medical services, involving several encounters (e.g., physician, caregiver, service personnel, hospital space and equipment service encounters), are periodicity used by patient (11). The medical service encounter could stimulate patients' positive experience of medical services and facilitate more interaction and two-way communication between patients and medical staff.

A review of the literature on service quality in the healthcare industry has primarily focused on (**i**) healthcare service quality and patient loyalty (12, 13); (**ii**) healthcare service quality and patient satisfaction (11, 14, 15); (**iii**) patient satisfaction and patient loyalty (12, 13, 16, 17); (**iv**) the physician-patient relationship and patient loyalty (18–20); and (**v**) the quality of the patient-patient relationship and patient loyalty (13, 16). In previous studies, research gaps still exist regarding whether the "service encounter" in healthcare can improve the relationship between patient quality, trust, and loyalty to hospital services, and aid in the development of the quality assessment by hospital service encounter. Therefore, from the viewpoint of healthcare encounters, the "Service Encounter Assessment Model" proposed by Chang et al. (21) and Gonzalez (2) was applied in this study to develop a research model and assessment scale to explore the relationship between the quality of hospital service and patients' trust and loyalty to hospital services after receiving medical service encounters. The objectives of this study, which was conducted in a large general public hospital, are as follows.

(1) To develop a service encounter and service quality scale that is suitable for the healthcare industry, using the "service encounter" perspective in conjunction with hospital service characteristics and service quality.
(2) To examine whether healthcare encounters enhance patient trust and loyalty.
(3) To explore whether improvements in hospital service quality positively affect patient contact, trust and loyalty to healthcare services.

LITERATURE REVIEW

Service Encounters

The service encounter is the most direct marker for patients and families to assess the quality of healthcare services, and is an important interface for patients to experience the professional competence of healthcare services. Stock et al. (22) proposed the theory of transformational behavior and applied it to the service industry, in which service encounters mainly involve human contact as the interface. They explored the different personal experiences of customers in interpersonal, technological, and professional service encounters. If a consumer has an unpleasant service encounter experience during the interaction with the service provider, "switching behavior" will occur (1, 23). Consumers seek out suitable and trustworthy service providers in a proactive manner. Therefore, the service encounter can be an important interface to enhance customer trust. Kim et al. (3) stated that medical services are human-centric, high contact, highly customizable, highly professional and onsite services that need to be patient-driven to enhance patient satisfaction, trust, and loyalty. Gonzalez (2) noted that patient-physician interactions include all healthcare encounters, as well as encounters with healthcare-staff-related equipment. The interactions between doctors, caregivers, and patients, as well as the spaces and equipment that patients are exposed to, are considered integral to the quality of healthcare services and affect patient satisfaction, trust, and loyalty. In conclusion, this study proposes that providing friendly healthcare encounters in hospitals can enhance patient trust, maintain a good doctor-patient relationship, and further increase patient loyalty.

Quality of Hospital Services

The service quality model "SERVQUAL" was developed by Parasuraman et al. (24) to explain the degree of difference between the perceived service quality (PSQ) and customer expectations in the service delivery process (10, 25). Parasuraman et al. (24) proposed SERVQUAL, which comprises 10 measurement dimensions: tangibles, reliability, responsiveness, credibility, courtesy, security, competence, communication, access, and understanding. Later, they employed factor analysis to reduce the 10 dimensions of the previous service quality model to 5 measurement dimensions: tangibles, reliability, responsiveness, assurance, and empathy, making it more suitable for application in other service industries (7, 10). Hsu (9) and Anabila et al. (26) proposed that the five dimensions of healthcare quality have positive effects on the customer's experience after encountering the service, and can also affect customer confidence and loyalty. Poor service quality can also lead to a loss of customer confidence and loyalty in addition to causing a poor post-encounter experience (27), and ultimately result in customer consumption switching behavior. Therefore, this study concludes that good service quality in hospitals will not only enhance patients' service encounter experience, but also improve patients' trust and loyalty to hospitals.

Patient Trust

Patients' trust stems from the real feelings that patients experience from the honesty, integrity and reliability of doctors and caregivers after encountering healthcare services, and patients tend to have higher trust and loyalty if they are more satisfied with their healthcare encounters. Sbaffi et al. (28) and Adeleke et al. (29) pointed out that trust refers to the patient's belief that his or her health needs can be adequately met by the healthcare provider, and the intention to build confidence and goodwill and willingness to establish a long-term relationship. The level of customer trust shows a linear relationship to customer loyalty, with a psychological state of trust and dependence arising when customers' actual service perceptions exceed expectations. Fatonah (18) mentioned that in the field of medical services, patients generate "quality perception/price perception > satisfaction > trust > loyalty," an in particular, when patients are regularly exposed to medical services, their "trust" has the strongest impact on "loyalty." Druica et al. (30) and Castaldo et al. (31) conducted interviews with patients regarding healthcare service encounters, and the nine services that are most important to patients' confidence were compiled and further developed into markers. The study also pointed out that patient confidence changes due to the professionalism of doctors and caregivers during healthcare service encounters. At the same time, the quality of service provided by doctors and caregivers can also cause changes in patient confidence. In this study, the nine patient trust markers of Druica et al. (30) and Castaldo et al. (31) were used as a reference for the patient trust scale. The markers in this study were further modified according to the characteristics of medical services. In summary, patients have higher loyalty when they have higher trust in hospital services after being exposed to medical services; contrariwise, patients have lower loyalty when they have lower trust in hospital services.

Patient Loyalty

Yang and Yuan (32) argue that customer loyalty will affect customers' buying behavior and that customer satisfaction is just an attitude expression and may not change buying behavior. Companies are familiar with the fact that as customer acquisition, customer retention, and customer profit growth are areas that companies need to work on, building customer loyalty to maintain a competitive advantage in the market is an important issue. Customer loyalty is one of the best intangible assets an organization can have, both at the attitudinal and behavioral levels, and it is a huge potential differentiator that can be a source of increased competitive advantage (33). However, for a company to have a high competitive advantage, it is important to carefully analyze and communicate effectively with each customer in order to fulfill the commitment to them, which is very important in the ever-changing market and helps to increase the level of customer satisfaction and loyalty (34). Huang et al. (35) noted that patient loyalty assessment can be divided into two aspects: attitudinal loyalty and behavioral loyalty. In terms of attitudinal loyalty, the main measures are: (1) primary willingness to visit: the tendency of patients to prefer a particular hospital when they have a medical need; (2) revisit willingness: the willingness of patients to visit the hospital again; and (3) loyalty-derived behavior: the willingness to recommend the hospital to others. With regards to behavioral loyalty, the main markers are the frequency of patients' visits to that hospital and the total number of visits.

HYPOTHESIS DEVELOPMENT

Hospital Service Quality, Service Encounter, Trust and Loyalty

Kim et al. (3) conducted an empirical study focusing on assessing the medical services' quality provided at a complementary and alternative medicine-oriented hospital using the service encounter approach, and analyzed the influence of treatment effectiveness on patient loyalty. The results indicated that the physician in a service encounter and service quality had a positive effect on treatment effectiveness. Yu et al.'s (27) study indicated that the impression of the facilities and environment in a service encounter directly impacted patient's satisfaction rates for interpersonal-based medical service encounters; in contrast, treatment effectiveness positively affected satisfaction regarding the medical service quality. Gonzalez's (2) study indicated that the most patient-physician interactions generated by healthcare encounters and exposed by patients were (1) healthcare-staff-related equipment; (2) interactions between doctors, caregivers, and patients; and (3) spaces and equipment. The service encounters in healthcare should be considered integral to the healthcare services quality and to their effect on patient

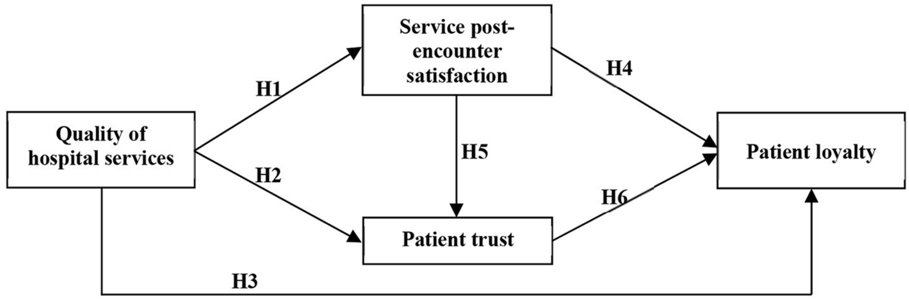

FIGURE 1 | Research model.

satisfaction, trust, and loyalty. From the above statements, the following hypotheses were developed:

H1: **Hospital service quality** has a significant positive effect on **service encounter**.
H2: **Hospital service quality** has a significant positive effect on **trust**.
H3: **Hospital service quality** has a significant positive effect on **doctor-patient loyalty**.

Service Encounter, Trust and Loyalty

Previous studies (2, 3) on service encounters from the perspective of patient-centered needs and concluded that interactions between doctors and caregivers, spaces, equipment that patients used, and service personnel quality influence patients' trust and loyalty to service encounters. The studies of Druica et al. (30) and Castaldo et al. (31) emphasize that healthcare service encounters are crucial to patients' confidence improvement. These studies also found that patient confidence differs depending on the professionalism of doctors and caregivers during healthcare service encounters. Simultaneously, the service encounter provided by doctors and caregivers can also cause increasing patient loyalty. Taken together, the following hypotheses were developed:

H4: **Service encounter** has a significant positive effect on **doctor-patient loyalty**.
H5: **Service encounter** has a significant positive effect on **doctor-patient trust**.

Patient Trust and Loyalty

Regarding the relationship between patients' trust and loyalty (13, 16–18, 36), findings show that the degree of patients' trust positively influences loyalty, and (13, 16, 17) prior trust directly and positively affects consequent satisfaction. Alhatti (16) and Fatima et al. (13) found that patients' trust under the perfect hospital service quality or service encounter can stimulate loyalty positively. Sbaffi et al. (28) and Adeleke et al. (29) showed that patients' trust results from the doctors and caregivers that provide adequate service to meet patients' health needs. Doctors and caregivers' goodwill and willingness can establish a long-term relationship of loyalty and trust. The level of patients' trust shows a linear relationship to their loyalty, with a psychological state of trust and dependence arising when patients' actual received service quality or service encounters exceed expectations. Medical service is an intangible product of service encounters; both medical care personnel and general service personnel must develop a trusting relationship with patients to enhance patient loyalty. Based on the above statements, the following hypothesis was developed:

H6: **Doctor-patient trust** has a significant positive effect on **doctor-patient loyalty**.

METHODOLOGY

Hypotheses Presented in a Model Diagram

In order to achieve the study objectives, this study focuses on the "service encounter" perspective and further develops the hospital service encounter and quality measurement scale by combining the characteristics of hospital services to investigate whether the quality of hospital services has a positive impact on patients' perceptions of healthcare services, trust and loyalty. Therefore, this study proposes a study model (**Figure 1**) consisting of hospital service quality, service encounter, and patient trust and loyalty dimensions. With regards to hospital service quality, this study is mainly based on the "service quality model" proposed by Parasuraman et al. (24), which is combined with the five measurement dimensions of medical service quality proposed by Chang et al. (37). With regards to service encounter, this study utilizes the "Service Encounter Assessment Model" Chang et al. (21) and Gonzalez (2) to develop a study model and scale, and modified it to take into account the characteristics of the healthcare service industry. This study also references the nine patient trust measurement markers Gabay (36) and Castaldo et al. (31) and the three trust measurement markers Huang et al. (35). This study also integrates the trust and loyalty-related components valued by patients in the healthcare service industry with the markers developed by the aforementioned scholars. Finally, this study utilizes a five-point Likert scale, where the scores 1–5 indicate *strongly disagree*, *disagree*, *no opinion*, *agree*, and *strongly agree*, respectively, as shown in **Table 1**.

The above discussion and literature suggest that the quality of healthcare services affects patients' perceptions of their satisfaction with hospital service encounters, as well as their trust

TABLE 1 | Hospital Service Encounter and Quality Measurement Scale.

Dimension	Measurement items	References
Tangibles	1. The hospital has safe facilities.	(11, 14, 15, 26, 37–39)
	2. The hospital has a barrier-free space design.	
	3. The hospital has a neat and comfortable environment.	
	4. The hospital has modern medical facilities.	
	5. The medical staff of the hospital are professionally dressed.	
Reliability	6. The doctors and nurses at this hospital can provide skilled and professional services.	
	7. Doctors at this hospital can give detailed information about the patient's condition and treatment.	
	8. The hospital's medical and nursing staff can provide prompt services to patients.	
	9. The medical staff at this hospital have a serious and genuine attitude toward their work service.	
Responsiveness	10. The hospital's medical staff is able to deal with patients' problems in a timely and prompt manner.	
	11. The hospital is able to clearly inform patients of the consultation and treatment process.	
	12. The hospital's doctors and nurses do not let their busy schedules delay meeting the patient's needs.	
	13. The medical staff of this hospital can provide medical advice in a timely and appropriate manner.	
	14. The medical staff at this hospital are always very helpful to patients.	
Assurance	15. The hospital's medical staff makes patients feel safe about their visits.	
	16. The professional performance of the medical staff at this hospital makes patients feel confident.	
	17. The doctors and nurses at this hospital have sufficient expertise to answer patients' questions.	
	18. The medical and nursing staff at this hospital generally have a good service attitude and courtesy.	
Empathy	19. The medical staff of this hospital will prioritize the best interests of the patient.	
	20. The medical staff at this hospital is sensitive to the privacy of the patient's visit.	
	21. The hospital's medical clinic hours are convenient for the average patient.	
	22. The hospital's medical staff is able to meet the special medical needs of patients.	
Physician **service encounters**	1 I think the doctors at that hospital will address my concerns.	(2, 21)
	2 I think the doctors at that hospital are reliable for me.	
	3 I think the doctors at this hospital have a good consultation attitude.	
	4 I think that the doctors at this hospital possess medical expertise.	
	5 I think the doctor at that hospital would recommend appropriate medication for me.	
	6 I believe that the doctors in that hospital show empathy for their patients.	
	7 I think the doctors at that hospital would tell the patients the treatment plan.	
Caregiver **service encounters**	8 I feel that the nurses at that hospital are reliable for me.	
	9 I think the nurses at that hospital will relieve me of my worries.	
	10 I believe that the nurses at this hospital show empathy for their patients.	
	11 I think the nurses in this hospital have a good attitude toward patient service.	
	12 I think the nurses in this hospital are professional.	
Service personnel **service encounters**	13 I find that the service staff at the hospital are reliable for me.	
	14 I think the service staff at that hospital can relieve me of my worries.	
	15 I believe that the attitude of the service staff at this hospital is beneficial to patients.	
	16 I feel that the service process in this hospital is efficient and convenient for patients.	
Space and equipment **service encounters**	17 I believe that the medical office of the hospital will give consideration to the privacy of the patients.	
	18 I think there are clear markers in the interior of that hospital.	
	19 I find that the toilets in the hospital to be clean and hygienic.	
	20 I find that the consultation rooms in the hospital to be spacious and bright.	
	21 I believe that the hospital has advanced medical equipment.	
Patient trust	1 I have complete faith that the doctors here will provide the best course of treatment for me.	(31, 36, 40)
	2 The doctor who sees me at this hospital will do his or her best to provide the medical care I need.	

(Continued)

TABLE 1 | Continued

Dimension	Measurement items	References
	3 I am not worried about putting my treatment solely in the hands of the doctors here.	
	4 The doctor who treated me at this hospital was very careful and attentive.	
	5 The doctors at that hospital are honest about all treatment options available to me.	
	6 The doctors at that hospital will think of the best way to treat me.	
	7 I believe the doctors at that hospital would never mislead me about anything.	
	8 I trust that the doctors at this hospital will usually use their best medical skills and efforts to treat their patients.	
	9 Overall, I can trust the doctors here completely.	
Patient loyalty	1 I prefer to go to the hospital for medical services	(35)
	2 I will choose the medical services provided by this hospital in the future.	
	3 I am happy to recommend the medical services provided by the hospital to friends and family.	

and loyalty toward doctors and healthcare workers. In addition, the interaction between doctors, nursing staff, and service providers with patients, as well as the space and equipment to which the patients are exposed, are healthcare encounters that enhance patient loyalty and trust. This study proposes the following hypotheses based on the above literature and research model.

H1: Hospital service quality has a significant positive effect on service encounter.
H2: Hospital service quality has a significant positive effect on trust.
H3: Hospital service quality has a significant positive effect on doctor-patient loyalty.
H4: Service encounter has a significant positive effect on doctor-patient loyalty.
H5: Service encounter has a significant positive effect on doctor-patient trust.
H6: Doctor-patient trust has a significant positive effect on doctor-patient loyalty.

Study Sample and Data Collection

According to the data released by the Statistical Information Center of the National Health and Health Commission, there are 1,441 grade-A tertiary hospitals in China. Among the proportion of Geriatrics (including elderly care services) set up in the grade-A tertiary hospitals in Jiangsu Province, 65.4% accounts for about 39% of the national total, ranking first in the country. Meanwhile, 77.4% of those over 60 years old and 85.3% of those over 80 years old have chronic diseases that require long-term medical service encounters.

Therefore, this study utilized the 2021 list of hospitals in Jiangsu Province, China. A total of 71 grade-A tertiary hospitals with geriatric departments were randomly selected. Due to the resource constraints of the study, only 20% of the hospitals were targeted for sampling and the following criteria were used for sample selection: (1) promoting comprehensive medical service quality management; (2) passing ISO 9000 international quality certification for more than two consecutive times; and (3) providing long-term medical service encounters for chronic diseases in the elderly. In this study, the above three criteria were used for the sample selection, mainly because the study population must have the implementation intensity in service quality, and 15 grade-A tertiary hospitals that meet the above conditions. To achieve the purpose of this study, whose main focus was medical service encounter, this study targeted patients with chronic diseases who needed to receive hospital service encounter on a regular basis (twice a week or more) as study subjects.

First, the 15 grade-A tertiary hospitals were asked through the telephone whether they would like to participate in this study, of which 6 agreed (sample passing rate of 40%), and these 6 served as representative study cases. Second, considering the elderly with a high incidence of chronic diseases in winter and the need for high-density medical service encounters, **100 pretest questionnaires** for elderly (family members were allowed to fill out the questionnaire) experiencing long-term medical services encounter were issued from November 28–30, 2021. In total, seven invalid questionnaires were eliminated. The demographic variables of the 93 valid samples showed that most of the respondents were male patients (52.7%), with an age range of 61–70 years old (25.8%), married (72.0%), and junior college education (33.3%) as the highest education level.

The Cronbach's α of each scale is 0.81 for **Tangibles**, 0.80 for **Reliability**, 0.84 for **Responsiveness**, 0.84 for **Assurance**, 0.80 for **Empathy**, 0.93 for **Physician service encounters**, 0.89 for **Caregiver service encounters**, 0.88 for **Service personnel service encounters**, 0.90 for **Space and equipment service encounters**, 0.94 for **Patient trust,** and 0.82 for **Patient loyalty**; all of the values exceeded the recommended minimum reliability of an α of 0.7 (41–43). The alpha value was not much larger than the total value when any item was deleted, indicating that the items on each scale were homogeneous. The results indicate a high correlation in internal data sampling, and the questionnaire had high reliability for use as a formal questionnaire. Then, 700 regular questionnaires were distributed to patients and family members of six of the selected tertiary hospitals from December 2021 to January 2022. Finally, this study collected a total of 634 questionnaires. After excluding 151 invalid questionnaires

(23.8%), the final number of valid questionnaires was **483**, for a valid questionnaire recovery rate of 76.2%.

RESULTS

Descriptive Statistics

A total of 483 valid questionnaires were collected. In terms of gender analysis, there were 263 males and 220 females. In terms of age, the largest number of respondents were **51–60** years old ($n = 213$) and **more than 61–70 years old** ($n = 104$). Regarding marital status, the number of married subjects was 294. In terms of education level, the largest number of respondents were junior college education ($n = 198$) and junior college graduates ($n = 147$). In terms of monthly income (retirement pay), the largest number of respondents ($n = 172$) earned 4,000–6,000 RMB retirement pay. In terms of occupation (work before retirement), the largest numbers of respondents were medical industry, accounting for 24.2% ($n = 117$) of the total number of respondents, followed by those working in the service industry before retirement, accounting for about 22.4% ($n = 108$) of the total number of respondents. In terms of the number of visits/per month, the highest number of visits was 1–5 times per month, accounting for 51.6% ($n = 249$) of the total population; the rest of the respondents had more than 5 visits per month, accounting for 40.4% ($n = 195$).

Exploratory Factor Analysis and Common Method Bias

To confirm whether the items in the initial questionnaire correspond to their potential constructs, this study used exploratory factor analysis (EFA) to assess the construct validity of the scale and examine whether an item needs to be deleted (44). We used the principal component analysis method to obtain the common interpretation variable between all the measurement questions; further, we applied the orthogonal rotation method of the equal maximum method, and took a factor load value higher than 0.4 as the basis for retaining an item. The 55 initial items in the original questionnaire were retained.

According to Qian et al. (45), the interpretation rate of the first factor should be <40%. The EFA of hospital service quality yielded a total of five factors, wherein the interpretation rate of the first factor was 31.05%. These five factors explain 74.10% of the amount of change, and the Kaiser-Meyer-Olkin (KMO) value was 0.98. The EFA of service post-encounter satisfaction yielded four factors, wherein the interpretation rate of the first factor was 32.62%. These four factors explain 73.73% of the amount of change, and the KMO value was 0.98. The EFA of patient trust and loyalty yielded a total of two factors, wherein the interpretation rate of the first factor was 38.18%. These two factors explain 71.43% of the amount of change, and the KMO value was 0.96. The above EFA results indicate that this study's sample were sufficiently internal to reasonably conduct EFA.

This study evaluated the presence of common method variance by the Harman single-factor test (46). The five factors of hospital service quality and the four factors of service post-encounter satisfaction were separately constrained to a single factor using factor analysis in SPSS. As per the unrotated factor solution, the percentage variance explained by the single factor of hospital service quality was 31.05%, service post-encounter satisfaction was 32.62%, patient trust was 34.28%, and patient loyalty was 38.13%. The above values are all lower than 50% (46).

TABLE 2 | Reliability analysis ($n = 483$).

Dimension	Cronbach's alpha coefficient
Tangibles	0.892
Reliability	0.893
Responsiveness	0.897
Assurance	0.882
Empathy	0.887
Physician **service encounters**	0.930
Caregiver **service encounters**	0.907
Service personnel **service encounters**	0.887
Space and equipment **service encounters**	0.898
Patient trust	0.943
Patient loyalty	0.844

*As can be seen from **Table 3**, the model fit markers are good, and all markers satisfy the fitness indicator except for the markers GFI and AGFI, which were close to 0.9, indicating that the model has a good fit (41–43, 47).*

TABLE 3 | Overall Study Model Fit Pointer Analysis ($n = 483$).

Fit	Name of marker	Judgment value	This study model	Marker conformance
Absolute fit	CMIN/DF	<3.000	2.152	Conforming
	GFI	>0.900	0.831	Close
	RMSEA	<0.080	0.048	Conforming
Incremental fit	AGFI	>0.900	0.810	Close
	CFI	>0.900	0.994	Conforming
	NFI	>0.900	0.989	Close
Parsimonious fit	IFI	>0.900	0.994	Conforming

Reliability, Validity, and Model Fit Test

We used the reliability analysis method for corresponding measurement and test, in order to test the reliability of the scale set in the questionnaire. The Cronbach's α coefficient shows that the reliability of all dimensions and variables exceeds 0.8, indicating good reliability of the entire scale (43). The results are shown in **Table 2**. **Table 3** shows that the model has a good fit index. Although the indexes GFI and AGFI are close to 0.9, other indexes meet the fit index, indicating a good model fit (41–43, 47).

Confirmatory Factor Analysis

Referring to research suggestions (43), this study conducted a confirmatory factor analysis to manage the covariance relationship between the measurement variables and their potential variables, and to test the convergence validity and discrimination validity of the measurement model. **Table 4** shows that the 55 observed variables in the formal questionnaire of this study reached a significant level ($T > 1.96$, $P < 0.05$), with the

TABLE 4 | Confirmatory factor analysis of the research model (n = 483).

Dimension	Measurement items	SFL	SE	t	SMC
Tangibles	1. The hospital has safe facilities.	0.79	0.03	20.14	0.62
	2. The hospital has a barrier-free space design.	0.82	0.03	21.41	0.67
	3. The hospital has a neat and comfortable environment.	0.81	0.03	21.11	0.66
	4. The hospital has modern medical facilities.	0.78	0.03	20.04	0.61
	5. The medical staff of the hospital are professionally dressed.	0.76	0.03	19.30	0.58
Reliability	6. The doctors and nurses at this hospital can provide skilled and professional services.	0.78	0.03	20.32	0.61
	7. Doctors at this hospital can give detailed information about the patient's condition and treatment.	0.78	0.03	20.15	0.61
	8. The hospital's medical and nursing staff can provide prompt services to patients.	0.79	0.03	20.70	0.63
	9. The medical staff at this hospital have a serious and genuine attitude toward their work service.	0.82	0.03	21.64	0.67
Responsiveness	10. The hospital's medical staff is able to deal with patients' problems in a timely and prompt manner.	0.82	0.03	21.60	0.67
	11. The hospital is able to clearly inform patients of the consultation and treatment process.	0.82	0.03	21.44	0.66
	12. The hospital's doctors and nurses do not let their busy schedules delay meeting the patient's needs.	0.84	0.03	22.31	0.70
	13. The medical staff of this hospital can provide medical advice in a timely and appropriate manner.	0.80	0.03	20.97	0.65
	14. The medical staff at this hospital are always very helpful to patients.	0.84	0.03	22.42	0.70
Assurance	15. The hospital's medical staff makes patients feel safe about their visits.	0.80	0.03	20.92	0.64
	16. The professional performance of the medical staff at this hospital makes patients feel confident.	0.84	0.03	22.80	0.71
	17. The doctors and nurses at this hospital have sufficient expertise to answer patients' questions.	0.78	0.03	20.30	0.61
	18. The medical and nursing staff at this hospital generally have a good service attitude and courtesy.	0.80	0.03	21.15	0.65
Empathy	19. The medical staff of this hospital will prioritize the best interests of the patient.	0.82	0.04	21.78	0.67
	20. The medical staff at this hospital is sensitive to the privacy of the patient's visit.	0.80	0.03	20.95	0.64
	21. The hospital's medical clinic hours are convenient for the average patient.	0.82	0.03	21.72	0.67
	22. The hospital's medical staff is able to meet the special medical needs of patients.	0.81	0.03	21.51	0.66
Physician **Service encounters**	1 I think the doctors at that hospital will address my concerns.	0.78	0.03	20.42	0.61
	2 I think the doctors at that hospital are reliable for me.	0.82	0.03	21.70	0.66
	3 I think the doctors at this hospital have a good consultation attitude.	0.81	0.03	21.49	0.66
	4 I think that the doctors at this hospital possess medical expertise.	0.83	0.03	22.29	0.69
	5 I think the doctor at that hospital would recommend appropriate medication for me.	0.83	0.03	22.10	0.68
	6 I believe that the doctors in that hospital show empathy for their patients.	0.83	0.03	22.14	0.68
	7 I think the doctors at that hospital would tell the patients the treatment plan.	0.78	0.03	20.32	0.61
Caregiver **service encounters**	8 I feel that the nurses at that hospital are reliable for me.	0.82	0.03	21.82	0.67
	9 I think the nurses at that hospital will relieve me of my worries.	0.81	0.03	21.30	0.65
	10 I believe that the nurses at this hospital show empathy for their patients.	0.82	0.03	21.90	0.68
	11 I think the nurses in this hospital have a good attitude toward patient service.	0.80	0.03	21.13	0.64
	12 I think the nurses in this hospital are professional.	0.82	0.03	21.74	0.67
Service personnel **service encounters**	13 I find that the service staff at the hospital are reliable for me.	0.80	0.03	21.06	0.64
	14 I think the service staff at that hospital can relieve me of my worries.	0.83	0.03	22.06	0.68
	15 I believe that the attitude of the service staff at this hospital is beneficial to patients.	0.83	0.03	22.24	0.69

(Continued)

TABLE 4 | Continued

Dimension	Measurement items	SFL	SE	t	SMC
	16 I feel that the service process in this hospital is efficient and convenient for patients.	0.81	0.03	21.24	0.65
Space and equipment **service encounters**	17 I believe that the medical office of the hospital will give consideration to the privacy of the patients.	0.79	0.03	20.43	0.62
	18 I think there are clear markers in the interior of that hospital.	0.80	0.03	21.06	0.64
	19 I find that the toilets in the hospital to be clean and hygienic.	0.80	0.03	20.91	0.64
	20 I find that the consultation rooms in the hospital to be spacious and bright.	0.83	0.03	22.04	0.68
	21 I believe that the hospital has advanced medical equipment.	0.78	0.03	20.20	0.61
Patient trust	1 I have complete faith that the doctors here will provide the best course of treatment for me.	0.76	0.03	19.52	0.57
	2 The doctor who sees me at this hospital will do his or her best to provide the medical care I need.	0.80	0.03	21.20	0.64
	3 I am not worried about putting my treatment solely in the hands of the doctors here.	0.81	0.03	21.47	0.65
	4 The doctor who treated me at this hospital was very careful and attentive.	0.84	0.03	22.71	0.70
	5 The doctors at that hospital are honest about all treatment options available to me.	0.82	0.03	21.78	0.67
	6 The doctors at that hospital will think of the best way to treat me.	0.78	0.03	20.50	0.62
	7 I believe the doctors at that hospital would never mislead me about anything.	0.77	0.03	20.02	0.60
	8 I trust that the doctors at this hospital will usually use their best medical skills and efforts to treat their patients.	0.82	0.03	22.00	0.68
	9 Overall, I can trust the doctors here completely.	0.83	0.03	22.42	0.69
Patient loyalty	1 I prefer to go to the hospital for medical services	0.74	0.03	18.57	0.55
	2 I will choose the medical services provided by this hospital in the future.	0.83	0.03	22.00	0.69
	3 I am happy to recommend the medical services provided by the hospital to friends and family.	0.84	0.03	22.43	0.71

SFL, standard factor loading; SE, standard error; $t > 1.96$ and $p < 0.05$ were significant; SMC = multiple correlation.

estimated parameter factor load higher than 0.5 (48, 49), and the square multiple correlations of each item more than 0.50 (50).

Convergent validity means that the observed variables in the same construct are highly correlated with each other; therefore, these observed variables can be used to measure the same construct (51). **Table 5** shows that the average variation extracted (AVE) from each facet in this study is between 0.708 and 0.747. Therefore, the measurement model of this study has convergent validity. The composite reliability ranges from 0.886 to 0.959, which conforms to the recommended value as 0.6 (50), indicating that the internal consistency of the model is high (44).

TABLE 5 | Convergent validity analysis ($n = 483$).

Dimension	CR	AVE
Tangibles	0.924	0.708
Reliability	0.922	0.747
Responsiveness	0.926	0.715
Assurance	0.916	0.731
Empathy	0.917	0.734
Patient trust	**0.959**	**0.723**
Physician **service encounters**	0.951	0.733
Caregiver **service encounters**	0.933	0.736
Service personnel **service encounters**	0.922	0.747
Space and equipment **service encounters**	0.927	0.718
Patient loyalty	**0.886**	**0.723**

The bold values indicated for distinguishing the dimension.

Correlation Analysis

Differential validity refers to the measurement of two different constructs. If the correlation degree of the two constructs is extremely low after correlation analysis, it suggest that the two constructs have differential validity (51). In terms of the discriminant validity test, this study starts with the number that the root mean square of AVE of each facet is greater than the correlation coefficient of each facet, and accounts for more than 75% of the total number of comparisons (52). First, after the correlation analysis of this study, there is a significant correlation between the constructs of the measurement model: the test of differential validity is conducted successively. The analysis results show that all constructs meet the judgment criteria, which proves that there are relevant but not the same factors among the constructs; thus, they have differential validity (**Table 5**).

The degree of correlation of the constructs was examined based on the Pearson correlation coefficient. All the variables were significantly positively correlated with each other at the significance level of 0.01 and the results of the correlation analysis illustrated the existence of correlation between the five dimensions of service quality and their values were all >0.700. The AVE square root value of each construct is greater than the correlation coefficient between the constructs and the scale has good comparative validity (43). The results are shown in **Table 6**.

TABLE 6 | Correlation analysis ($n = 483$).

	1	2	3	4	5	6	7	8	9	10	11
1. Tangibles	**0.841**										
2. Reliability	0.744**	**0.864**									
3. Responsiveness	0.811**	0.835**	**0.845**								
4. Assurance	0.789**	0.857**	0.844**	**0.855**							
5. Empathy	0.773**	0.842**	0.834**	0.849**	**0.857**						
6. Physician service encounters	0.767**	0.840**	0.815**	0.852**	0.852**	**0.866**					
7. Caregiver service encounters	0.734**	0.815**	0.785**	0.848**	0.844**	0.859**	**0.868**				
8. Service personnel service encounters	0.766**	0.826**	0.794**	0.834**	0.826**	0.851**	0.856**	**0.864**			
9. Space and equipment service encounters	0.767**	0.810**	0.781**	0.811**	0.822**	0.857**	0.849**	0.844**	**0.888**		
10. Patient trust	0.778**	0.824**	0.803**	0.848**	0.847**	0.811**	0.850**	0.889**	0.871**	**0.850**	
11. Patient loyalty	0.719**	0.756**	0.743**	0.778**	0.780**	0.825**	0.810**	0.811**	0.803**	0.848**	**0.850**

Refers to $p < 0.05$; **refers to $p < 0.01$; ***refers to $p < 0.001$;* ***numbers in bold* *are square roots of AVE.*

Regression Analysis of Hospital Service Quality and Service Encounters

This study used linear regression to verify whether hospital service quality has an effect on healthcare contact, for which 10 separate models were developed. In this study, subject background data (including: gender, age, education, and frequency) were set as control variables, **hospital service quality** variable (including: tangibles, reliability, responsiveness, assurance, and care) were set as independent variables, and **post-service encounter satisfaction** variables (including physician service encounter, nursing staff service encounter, service staff service encounter, and space and equipment service encounter) were set as dependent variables for linear regression analysis. The results of the analysis are shown in **Table 7**. Models M1, M3, M5, M7, and M9 all showed that respondent age and number of visits have partially significant effects on health service encounter, indicating that the model was influenced by some of the respondent background data. In addition, models M2, M6, and M8 show that hospital service quality tangibles, reliability, responsiveness, assurance, and empathy have significant positive effects on service encounters with physicians, providers, and space and equipment, whereas model M4 only shows that responsiveness, assurance, and empathy have significant positive effects on service encounters with nursing staff; finally, model M10 shows that hospital service quality has a significant positive effect on patient service ($p < 0.001$), with a β value of **0.919**. This indicates that the higher the patient's perception of **hospital service quality**, the higher the patient's **satisfaction** with the post-encounter **service experience**, supporting Hypothesis H1.

Regression Analysis of the Effects of Hospital Service Quality on Patient Trust and Loyalty

To verify the effect of hospital service quality on trust, this study used linear regression equations to develop six separate models. In this study, subject background data were set as the control variables, hospital service quality was set as the independent variable, and patient trust and loyalty were set as dependent variables. The results of the analysis are shown in **Table 8**. Model M1 shows that age and number of visits have a significant effect on patient trust; model M4 shows that the number of visits has a significant effect on patient loyalty. Models M2, M3, M5, and M6 show that hospital service quality has a significant positive effect on patient trust and loyalty, with models M3 and M6 having a beta-value of **0.881** and **0.811**, respectively, and a p-value of <0.001. This result indicates that the higher the quality **of hospital services**, the higher the patient trust and loyalty. Therefore, Hypotheses H2 and H3 of this study are supported.

Regression Analysis of Post-encounter Hospital Service Satisfaction and Patient Trust and Loyalty

This study used linear regression equations to validate the effect of ***post*-service encounter satisfaction** on patient trust and loyalty in hospitals, and four separate models were developed. In this study, respondent background data were set as the control variables, service encounter (including: physicians, nursing staff, service staff and service encounter such as space and equipment) was set as the independent variable, and patient trust and loyalty were set as the dependent variables. The results are shown in **Table 9**. In model M1, respondent age and number of visits had a significant effect on patient trust, while in M4, the number of visits had a significant effect on patient loyalty. The results of models M2 and M5 show that patient satisfaction after service encounter has a significant positive effect on patient trust and loyalty, of which the β-values of models M3 and M6 are **0.930** and **0.852**, respectively, and p-values are <0.001. This result indicates that the improvement in **hospital's satisfaction after service encounter** can enhance patients' trust and loyalty, supporting Hypotheses H4 and H5.

Regression Analysis of Patient Trust and Loyalties

This section validates the effect of patient trust on patient loyalty, for which two models were developed. In this study, respondent background data was set as the control variable, patient trust as

TABLE 7 | Regression analysis of hospital service quality and satisfaction with the experience after service encounter ($n = 483$).

Dependent variable	Physician service Encounters		Caregiver service encounters		Service personnel service encounters		Space and equipment service encounters		Service Encounters	
	M1	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**	**M8**	**M9**	**M10**
Control variables										
Sex	–0.036	**–0.0**52**	0.011	–0.009	0.052	0.040	0.008	–0.003	–0.009	–0.001
Age	**–0.114***	–0.037	**–0.135***	**–0.055***	–0.094	–0.020	**–0.105***	–0.033	**–0.118***	**–0.045***
Education level	–0.017	–0.023	–0.053	**–0.050***	0.009	–0.003	–0.028	–0.043	–0.023	**–0.046***
Number of visits	–0.065	0.030	**–0.134****	–0.037	**–0.127****	–0.034	**–0.110***	–0.018	**–0.115***	–0.024
Independent variable										
Tangibles		**0.076***		0.018		**0.126****		**0.181*****		
Reliability		**0.106***		0.046		**0.105***		**0.107***		
Responsiveness		**0.194*****		**0.153****		**0.211*****		**0.170****		
Assurance		**0.280*****		**0.362*****		**0.253*****		**0.184****		
Empathy		**0.305*****		**0.350*****		**0.243*****		**0.290*****		
Quality of hospital services										**0.919*****
R^2	0.013	0.809	0.026	0.784	0.025	0.773	0.017	0.751	0.020	0.852
AdjR^2	0.005	0.805	0.018	0.780	0.017	0.769	0.009	0.746	0.012	0.850
F	1.584	222.598***	3.170	191.303***	3.040	179.111***	2.058	158.455***	2.452	548.070***
Durbin-Watson		1.958		1.771		1.694		1.685		1.804

**Refers to p < 0.05; **refers to p < 0.01; ***refers to p < 0.001. The bold values indicated for significant effect.*

TABLE 8 | Hospital service quality and trust and customer loyalty regression analysis ($n = 483$).

Dependent variable	Patient trust			Patient loyalty		
	M1	M2	M3	M4	M5	M6
	β	β	β	β	β	β
Control variable						
Sex	0.014	−0.001	0.004	0.006	−0.008	−0.003
Age	**−0.131***	**−0.550***	**0.0–61***	−0.079	−0.010	−0.015
Education level	0.013	0.005	−0.008	0.043	0.034	0.023
Number of visits	**−0.118***	−0.023	−0.031	**−0.126****	−0.041	−0.046
Independent variable						
Tangibles		**0.135*****			**0.132****	
Reliability		**0.093***			**0.114***	
Responsiveness		**0.119***			0.089	
Assurance		**0.286*****			**0.243*****	
Empathy		**0.317*****			**0.297*****	
Quality of hospital services			**0.881*****			**0.811*****
R^2	0.027	0.798	0.791	0.023	0.676	0.671
AdjR^2	0.019	0.794	0.789	0.015	0.670	0.667
F	3.334	207.267***	361.126***	2.808	106.568***	194.378***
Durbin-Watson		1.888	1.891		1.872	1.877

*Refers to $p < 0.05$; **refers to $p < 0.01$; ***refers to $p < 0.001$. The bold values indicated for significant effect.

TABLE 9 | Regression analysis of post-service encounter satisfaction with patient trust and loyalty ($n = 483$).

Dependent variable	Patient trust			Patient loyalty		
	M1	M2	M3	M4	M5	M6
	β	β	β	β	β	β
Control variables						
Sex	0.014	0.013	0.006	0.006	−0.008	−0.002
Age	**−0.131***	−0.023	−0.021	−0.079	0.028	0.021
Education level	0.013	0.030	0.035	0.043	0.030	0.**063***
Number of visits	**−0.118***	−0.021	−0.011	**−0.126****	−0.022	−0.028
Independent variable						
Physician service encounters		**0.397*****			**0.321*****	
Caregiver service encounters		**0.144****			**0.182****	
Service personnel service encounters		**0.246*****			**0.193****	
Space and equipment service encounters		**0.188*****			**0.209*****	
Service Encounters			**0.930*****			**0.852*****
R^2	0.027	0.879	0.875	0.023	0.735	0.734
Adjusted R^2	0.019	0.876	0.873	0.015	0.731	0.732
F	3.334	428.548***	666.221***	2.808	164.405***	263.867***
Durbin-Watson		1.956	1.940		2.003	1.998

*Refers to $p < 0.05$; **refers to $p < 0.01$; ***refers to $p < 0.001$. The bold values indicated for significant effect.

the independent variable, and loyalty as the dependent variable. The results are shown in **Table 10**. In Model 1, it was found that the number of visits to the patient had a significant effect on patient loyalty, while Model 2 shows that patient trust enhancement has a significant positive effect on loyalty. This result indicates that the quality of hospital services and service encounter can enhance patient trust as well as patient loyalty. In particular, Model 2 showed that the effect of patient trust on loyalty reached significance ($p < 0.001$) with a beta value of **0.858**, supporting Hypothesis H6.

TABLE 10 | Trust and customer loyalty regression analysis (*n* = 483).

Dependent variable	Patient loyalty	
	Model 1	Model 2
	β	β
Control variable		
Sex	0.006	−0.006
Age	−0.079	0.033
Education level	0.043	0.032
Number of visits	**−0.126****	−0.025
Independent variable		
Patient trust		**0.858*****
R^2	0.023	0.739
Adjusted R^2	0.015	0.736
F	2.808	269.449***
Durbin-Watson		2.083

***Refers to p < 0.01; ***refers to p < 0.001. The bold values indicated for significant effect.*

TABLE 11 | Estimated values of hypothetical path parameters of theoretical structure model (*n* = 483).

Path	H	S	SE	*t*-value
Quality of hospital services → service encounters	H1	0.96	0.07	13.36
Quality of hospital services→ patient trust	H2	0.93	0.05	18.37
Quality of hospital services → patient loyalty	H3	0.90	0.05	16.99
Service encounters → patient loyalty	H4	1.07	0.10	11.04
Service encounters → patient trust	H5	0.97	0.13	7.22
Patients trust → patient loyalty	H6	0.77	0.25	3.14

H, research hypothesis; S, standard coefficient; SE, standard error.

Verification of Structural Equation Model

In this study, LISREL 8.80 was further used for structural equation model analysis. It is assumed that the model has a good matching degree (df = 1415,$\chi 2 = 2995.78$, $\chi 2/\text{df} = 2.12 < 5$, RMSEA = 0.048, NNFI = 0.99, CFI = 0.99) (44, 51). The hypothesis of this study is verified by the estimated value of path parameters in the hypothetical structure model. When the t value of parameters is >1.65 ($p < 0.05$, single tail), the hypothetical path is established (**Table 11**). There are six hypothetical paths of the structural model, and the final six are established. The above indicates that hospital service quality does have a directly related impact on post service satisfaction, patient trust and patient loyalty; satisfaction after encounter does have a direct impact on patient trust and patient loyalty; patient trust does have a directly related impact on patient loyalty.

In addition to the analysis of verifying the research hypothesis (direct effect), this study also discusses the indirect effect and total effect between facets for confirming the existing mediating effect in the research hypothesis (51). It can be seen from **Table 12** that the indirect effect of hospital service quality on patient trust is significant, which indicates the phenomenon of patients' trust in hospital service quality. It will be more logical to take "hospital's satisfaction after service encounter as an **intermediary variable**. The indirect effect of 'hospital service quality' and 'hospital's satisfaction after service encounter" on "patient loyalty" is significant, which means that patients are loyal to the third-class hospital. Once there is the phenomenon of "satisfaction after service encounter" and "patient trust" as the **intermediary variables**, the explanation will be more reasonable. The above indicates that "satisfaction after service encounter" and "patient" **are indeed linked and indispensable** in the relationship between service quality and patient loyalty in third-class hospitals.

CONCLUSION AND RECOMMENDATIONS

Conclusion

This study was conducted with the service encounter evaluation model (14, 15) Chang et al. (21) Gonzalez (2) as a theoretical basis, and the study model and scale were further developed by combining the characteristics of healthcare service quality to explore the relationship between patients' service quality, trust, and loyalty to the hospital after patients' healthcare service encounters. The results of this study are shown in **Figure 2**. First, the results of the H1 analysis showed that the quality of hospital services to patients positively and significantly affects patients' perceived satisfaction after encounter with healthcare services, which means that even if the front-line doctors, nursing and service personnel try to do a good job in contacting patients, if the quality of hospital services is poor, this leads to a poor post-encounter experience of the services provided by the hospital. In other words, good service quality in hospitals also enables doctors, nurses, and service providers to create better perceptions of the service encounter among patients. In particular, the tangibles, reliability, responsiveness, assurance, and empathy of hospital service quality have a significant positive impact on service encounters with physicians, staff, space and equipment.

Second, the results of the H2 and H3 analysis revealed that the quality of services provided by frontline doctors, nurses, and service personnel in hospitals affects patients' trust and loyalty. At the same time, the results of the H4 and H5 analysis indicate that good service encounter perceptions regarding doctors, nurses, and service staff enhance patients' trust and loyalty toward doctors, nurses, and service staff. When a hospital provides high quality services, affords patients good service encounters, and gains high trust and loyalty from patients, this not only improves the quality of hospital care, but also makes patients feel satisfied and highly cooperative with the prescriptions and recommendations arranged by doctors.

In addition, a regression analysis of patient trust on loyalty showed that tangibles, reliability, responsiveness, assurance, and empathy of service quality all significantly affected patient trust. Patients were most concerned about medical equipment, the professionalism of medical staff, attitude, and consideration of patients' needs, and mistakes in these factors would reduce patients' trust, further leading to a decrease in patient loyalty. This study also found that the impact of patients' responses to service quality in terms of trust was very low and insignificant, indicating that hospital staff must improve service efficiency to hasten the resolution of patients' problems and make customers

TABLE 12 | Analysis of indirect effect and total effect ($n = 483$).

Dependent variable	Independent variable	Indirect effect			Total effect			Supported or not
		SEF	SE	*t*	SEF	SE	*t*	
Service encounters	Quality of hospital services	–	–	–	0.96	0.07	13.36	–/Supported
Patient trust	Quality of hospital services	1.02	0.10	10.06	0.93	0.05	18.37	Supported/Supported
	Service encounters	–	–	–	1.07	0.10	11.04	–/Supported
Patient loyalty	Quality of hospital services	0.86	0.13	6.44	0.90	0.05	16.99	Supported/Supported
	Service encounters	0.82	0.27	3.03	0.97	0.13	7.22	Supported/Supported
	Patient trust	–	–	–	0.77	0.25	3.14	–/Supported

SEF, standardization coefficient; SE, standard deviation; t, significant level.

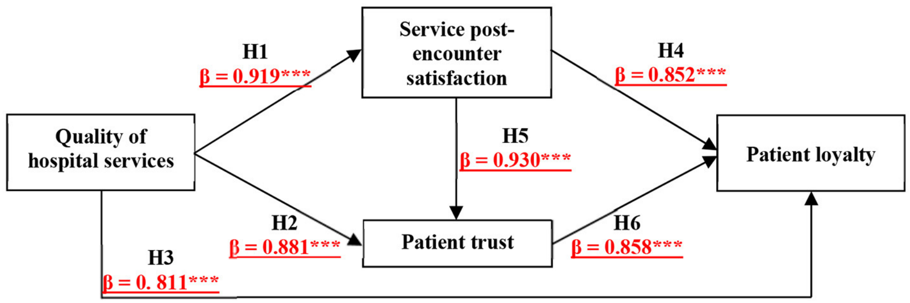

FIGURE 2 | Research model analysis results. The symbol *** indicated the significant coefficients of paths.

feel convenient and at ease. At the same time, the reliability of service quality in terms of patient loyalty has a very low impact and is not significant, indicating that the professional and medical skills of the medical staff need to be improved. It is recommended that the hospital conduct regular professional training and medical knowledge lectures for doctors in the hope of improving the professional skills of the medical staff and enhancing the hospital's own competitiveness.

Finally, satisfaction after the service encounter also significantly affects patient trust, so hospitals that implement good medical equipment and overall comfort, robust care, warm care, and friendly healthcare staff can significantly increase patient trust and loyalty. The results of the H6 analysis showed that the quality of services provided by the hospital significantly enhances patient trust and further increases patient loyalty to the hospital. The results of this study also revealed that the tangibles and reliability of service quality had a very low and non-significant impact on the service encounter with nursing staff, indicating that the medical equipment, environment, and medical professionalism of healthcare staff need to be improved when encountering patients. Additionally, a comparison of the strengths of the service encounter perspective between this study and previous studies is described clearly in **Table 13** to better understand the research novelty.

Managerial Implications

The five dimensions of hospital service quality can positively and directly affect the performance of post-service encounter satisfaction almost across the board, except for tangibles and reliability, which have no significant effect on post-service encounter satisfaction of nursing staff. This may be because caregivers are predominantly presented as assisting physicians from the sidelines, causing patients to dilute their perceptions of these two dimensions of the caregiver service in scenarios where physicians and caregivers are both present. For hospital management, the focus could be on the direct assistance provided by the nursing staff to the patient, in which nursing staff not only share the work of the physician, but also better complement nursing and medical care.

The five dimensions of hospital service quality also positively and directly impact patient trust and loyalty almost across the board, with the exception of the responsiveness dimension, which has no significant impact on patient loyalty. This may be because patient loyalty is more focused on the ability to resolve a condition carefully than on the expectation that the physician will complete the consultation in a short period of time. For hospital management, consideration should be given to encouraging physicians to extend consultation durations and limiting the number of patients registered by some physicians.

All four dimensions of post-encounter satisfaction positively and directly impact patient trust and loyalty, and all have the greatest impact on post-encounter satisfaction with physician services. Hospital administrators should continue to maintain the quality of not only the physician talent they employ, but also the quality of the nursing staff, service staff, space and equipment, and the maintenance of updated hardware.

Finally, in an era of increasing competition in the medical services industry, patients retain a preference for tertiary hospitals because of the greater injection of public resources into the medical standards of their professionals and facilities,

TABLE 13 | The comparison of the strengths of this study with previous studies using the service encounter perspective.

Source	The previous studies
Fatima et al. (13); Rostami et al. (12)	Focused on an assessment of patient loyalty using service quality.
Al-Neyadi et al. (14); Behdioglu et al. (15); Owusu Kwateng et al. (11)	Focused on an assessment of patient satisfaction by engaging service quality.
Alhatti (16); Fatima et al. (13); Miao et al. (17); Rostami et al. (12)	Confirmed patient satisfaction and patient loyalty as a positive relationship
Fatonah (18); Hajikhani et al. (19); Huang et al. (20)	Established the relationship between physician-patient and patient loyalty
Alhatti (16); Fatima et al. (13)	Established the relationship between the quality of the patient-patient and patient loyalty
Source	**Strengths of the present study**
Present study	Proposed a comprehensive research model based on the "Service Encounter Assessment Model," and integrating tertiary hospital characteristics. Provided an evidence-based practice study using a service encounter perspective for representative case tertiary hospitals in China. Remedied research gaps of previous studies, the "service encounter" perspective in healthcare is utilized to explore the relationship between hospital services quality, patient trust, and patient loyalty. We studied elderly patients, who experience long-term medical service encounters, generate experience feelings, which positively influence patient trust and loyalty.

which boosts patients' confidence that they will receive good medical treatment. Therefore, the accreditation system of tertiary hospitals will enable them to maintain their designation so that they can sustainably provide the appropriate level of care and contribute to society.

In China, regardless of being laypersons or medical workers, when it comes to hospitals, everyone agrees that grade-A tertiary hospitals are the best. These hospitals are the first choice to treat chronic diseases and physical discomfort. Grade-A tertiary hospitals are also the first choice for the employment of doctors and nurses. Given the continuous improvement of patient awareness, medical demand is more significant than medical supply. In addition, the frequent occurrence of various large-scale environmental, infectious diseases, and chronic diseases in recent years, the medical management system of grade-A tertiary hospitals should take the most streamlined human resources for the quality and quantity of medical services and adopt a "patient-oriented" business philosophy. In this study, we suggest that hospitals create "patient satisfaction" and "service encounters" for improving "patient trust" and "patient loyalty" to realize the ultimate ideal of sustainable operations of medical institutions.

Theoretical Implications

Population aging is a social problem faced by many countries, including China. The consequent pressure on the medical system comes from the increase in elderly patients with chronic diseases. Elderly patients with chronic conditions are bound to seek medical resources periodically. In China, grade-A tertiary hospitals are the best places to provide medical treatment for such people. Therefore, medical service contact has become an essential issue between grade-A tertiary hospitals and elderly patients with chronic diseases. Elderly patients with chronic diseases traditionally prefer physical medical experiences and are more sensitive to people and things in biological and medical treatment than young people. This study employed post-service encounter satisfaction and trust as mediating variables and explained the effector pathways of hospital service quality with fairly positive and significant results. Hospital service quality is intangible, manifested through tangible hospital personnel (doctors, nursing staff, service staff), as well as space and equipment, and perceptions of patients, which in turn leads to patients' trust in hospital care and ultimately to loyal attitudes.

This result adds to the service quality theory. Discussions on service quality in the past frequently refer to the impact of the perceived tangibles, reliability, responsiveness, assurance and empathy of the service provider on subsequent constructs, such as trust and loyalty, and few explore the actual people, events and variables that the service recipient encounters, such as medical staff, service personnel, and space and equipment. The mediating role of post-service encounter satisfaction in this study specifically indicates that regardless of the degree of medical service quality provided by medical institutions, hospital service quality can affect loyalty not only directly and positively (direct effect, 0.811) and through patient trust (indirect effect, $0.881 \times 0.858 = 0.756$), but also from post-service encounter satisfaction (indirect effect, 0.783, $0.919 \times 0.852 = 0.783$), and service post-encounter satisfaction triggering patient trust and loyalty (indirect effect: 0.733, $0.919 \times 0.930 \times 0.858 = 0.733$), thus providing a complete explanation of the mechanisms by which hospital service quality will result in patient loyalty. Therefore, grade-A tertiary hospitals will strive toward achieving customer orientation.

Study Limitations and Suggestions for Future Studies

From the results of the overall model analysis of this study, we found that patients showed a positive relationship between hospital service quality, post-service encounter satisfaction, trust, and loyalty for the six tertiary hospitals selected for the study. This study also confirmed that hospital service quality and the post-service encounter satisfaction of healthcare personnel play a decisive and important role in the improvement of patients' trust and loyalty. However, this study has some limitations, such as in the selection of scales. For example, there may be a potential effect of nursing staff on patient trust and loyalty under the influence of service encounter and the factor of patient-medical staff relationship commitment. In addition, there could be a possible mediating effect on patient-medical staff relationship commitment between the quality of healthcare services and patient satisfaction. Therefore, it is suggested that future studies explore the patient-medical staff relationship in greater detail. In summary, this study suggests that hospitals must focus on enhancing service quality, as good service quality is more effective in ensuring patient satisfaction with the service encounter and increasing patient trust. When patients are highly cooperative with doctors in arranging prescriptions and advice, the higher the loyalty to doctors, nurses, and service providers, which means that patients feel convenient and reassured, and strengthen their dependence (5, 15). With such a positive feedback loop, it is believed that the recovery rate of the patients will be improved.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

A-JS: writing—original draft and revising, research conceptualization, methodology, and data analysis. Y-FH: research conceptualization, methodology, supervision, coordinating tasks, and writing—revising the manuscript. G-YL and MY: formal analysis and validation, investigation, writing—revising the manuscript, and final approval of the version. W-YL, Y-YD, and Z-HS: research administration for the empirical project, resources, investigation, interpretation of data, writing—revising the manuscript, and final approval of the version. YW: communication with research objects, data collection, writing—revising the manuscript, and final approval of the version. All authors read and approved the final manuscript and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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Analysis of the Quantitative Evaluation of the Public Medical and Health System Costs During Pandemic Governance: Investigation Based on COVID-19

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It is of great reference significance for broadening the research perspective of pandemic governance, improving the efficiency of pandemic governance and the credibility of the government, to scientifically measure and analyze the public medical and health system costs. This article takes the typical case "pandemic prevention and control event of S city, China" as the research background. First, the concept of public medical and health system costs during pandemic governance is defined. Then, the public medical and health system costs are embedded into the pandemic governance system, and the generation process of the public medical and health system costs in the actual situation are investigated. Furthermore, through in-depth interview, multi-case grounded theory and fuzzy subordinate function analysis, the scientific construction of the public medical and health system cost index system are completed. Finally, based on G1 method/entropy method combined with weighting and fuzzy comprehensive evaluation method, the public medical and health system costs of the pandemic prevention and control events of S city is measured. The results show the following: (1) it is important that good single dimensions and reliable indicators are embodied in the public medical and health system costs scale. Among them, the behavioral public medical and health system costs of the masses is the largest proportion of all indicators; (2) after the pandemic prevention and control event is over, the public medical and health system cost are difficult to repair, and some lagging ideas and behaviors shown by local governments lead to a continuous expansion of the public medical and health system costs associated with pandemic governance; and (3) local governments should not conceal information asymmetry. Instead, local governments should give greater freedom to other actors to deal with pandemic governance, and governance entities should cooperate with each other. This will mitigate the effect of public medical and health system costs. Corresponding policy recommendations are proposed.

Keywords: pandemic governance, public medical and health system costs, quantitative evaluation, the grounded theory, the combinational evaluation of subjective and objective method

INTRODUCTION

It can be said that the prevention and control of COVID-19 is a centralized test of the emergency management system and governance capacity of various countries. Although China's current pandemic prevention and control situation continues to show good momentum, the pandemic prevention and control process has exposed a series of problems: public opinion risk monitoring and publicity guidance lag, and the public psychological intervention mechanism is absent (1). There are also some prominent problems. For example, the organizational and institutional systems of pandemic prevention and control are not fully connected and coordinated, and the various prevention and control agencies remain relatively independent in their operations. It should be noted that many public functions involved in pandemic prevention and control are not fully divided, and problems of overlapping or lagging gaps still exist to varying degrees (2). In addition, the partial defects and implementation errors of the emergency prevention and control system have resulted in an unbalanced distribution of benefits and costs, prominent contradictions between economic development and pandemic prevention and control, and frequent conflicts of rights protection incidents in pandemic prevention and control. These phenomena will reduce the credibility of a government and the public satisfaction, resulting in an unnecessary waste of the public medical and health system resources (intangible resources) (3). The government must increase the public medical and health system resource inputs to achieve pandemic governance goals, which constitutes the public medical and health system costs during pandemic governance. The process of consuming public medical and health system resources related to pandemic concerns is accompanied by complex issues, such as ethics, government and citizen behavior, and legitimacy, and it difficult for traditional governance approaches to effectively deal with multiple conflicting interests in pandemic governance (4). Medical system costs for pandemic prevention and control involve complex issues such as public demand and political legitimacy, and the effectiveness of governance depends on public recognition, participation, and support (5). Public health is a major system issue. Therefore, the study of the public medical and health system costs associated with pandemic governance problems requires multidisciplinary theories and methods, such as public crisis management, government economics, and social security, but it also should pay attention to obtaining control instruments from a multi-disciplinary and multiple-research perspective.

DEFINITION OF CONCEPTS

The pandemic governance issues have risen to the level of system issues, and has become an important part of the governance system of many countries. The introduction of political science, public administration, and economics in pandemic governance are conducive to help the government to determine an effective and precise path with respect to pandemic control precisely and effectively. With the increasing diversity and complexity of public affairs, the importance of the cost of system is a concept that has emerged repeatedly. David Easton (6) proposed that, for a public system to function properly, it must have some resources to serve as a driving force and foundation (6). Harold D. Lasswell (7) and Dennis Wrong (8) subsequently continued to deepen the interpretation of the concept of system resources, arguing that elements such as the institutional mechanisms, organization and culture are a means to influence system objects that can be constantly consumed and lost (7, 8). The government needs to have and consume certain public medical and health system resources, and thus reflects the value of its existence and achieves its pandemic governance goals (9). It can be divided into "tangible resources" (e.g., economic resources), which are materially consumed, and "intangible resources" (e.g., public medical and health system resources), due to the hidden characteristic of intangible costs, they are often ignored by the government, examples of which include exist objectively organizational resources, and the system of democracy by the government (10). Under the coercive character of the governmental system, the institutional discrimination, uneven distribution of governmental public goods supplies and benefits, and unfair procedures will trigger protests from various interest entities (11). Therefore, a government that values and effectively uses intangible resources will appear more stable in its legitimacy base and public security (12).

In the process of pandemic prevention and control, various complex and comprehensive cost containment strategies are being developed across the most regions tailored to his national needs (13). The governance of the pandemic is regarded as a public choice process in the decision-making of local governments. Local governments as Rational Economic Man and agents have the necessity to provide the necessary public products for the public to carry out the pandemic prevention and control. Various "transaction costs" will generate in the process of governance, so the "care" for all stakeholders fairly cannot be realized. However, the design of the public health and medical system will be influenced by all stakeholders through various channels. The disturbance of the optimality of the public health and medical system, the consumption of the limited system resources in the pandemic prevention and control, and the generation of certain social risks will be caused by the interest expression and demands of all stakeholders. The reality and system defects promote the formation of the social risk. Once it is embedded in the social structure, the elimination of its substantive risk will not be realized, and the possibility of evolution or even mutation will exist. The external factors such as the media will easily influence the public's perception in the pandemic prevention and control. No matter it is scientific and reasonable or not, the public will firstly "amplify the problem" and actively pursue risks instead of considering the outcome, since the greater benefits will be brought to them. What is worse is that the potential risks of pandemic prevention and control derived from it will evolve into social risks.

The local government, as the institution that ultimately allocates resources in pandemic, needs to comprehend considerable amounts of information and conduct a scientific analysis of pandemic governance when governing the pandemic, and convene relevant experts to discuss and scientifically evaluate the feasibility and operability of various options (14). It also needs to assess the risks, public opinion, and benefits associated with implementing a certain option (15). When the validated decisions are put into practice, the waste and loss of public medical and health system resources caused by unscientific decisions can be avoided. In addition, the interests of the public and other governance entities have led to the selective allocation of public medical goods supply and delicacy domination of medical system resources, which makes neglected medical system resources constantly visible with the expression of public demands (16), which has meant that public medical and health system resources are constantly associated with the expression of public demands or the occurrence of protests. With the development of democratization and the increase in public awareness of pandemic rights and participation, the public's understanding of public medical and health system resources has gradually changed to materialization (17). Based on the above analysis, the public medical and health system costs are the system resources consumed by the government or others in the process of exercising political power and taking political actions in order to achieve pandemic governance and obtain public medical and health governance performance, as well as the public medical and health system resources to be borne by society and organizations. The consumption of these system resources will have various impacts on the society. The public medical and health system costs are intangible and scarce costs, which are difficult to manifest before accumulating to a certain extent and have the hidden characteristic, which contain the following elements:

(1) The public medical and health institutional policy costs (institutional policy costs for short). Such as institutional laws and policies and regulations in the institutional system of pandemic governance (18).
(2) The public medical and health system organizational costs (system organizational costs for short). Such as the government, social organizations, and relevant staff, etc. which together form the system organization that guarantees the effective functioning of pandemic governance (19).
(3) The public medical and health social perceptive costs (social perceptive costs for short). Such as the publicity and education costs, ideals beliefs, and social psychology, which could make the long-term behavior of social entities produce pandemic governance identity (20).
(4) The public medical and health mass behavioral costs (mass behavioral costs for short). The treatment of COVID-19 control mass events is a complex and long-term systemic project that requires long and uninterrupted public participation and support (21). The public satisfaction, identity, and trust are also important.

LITERATURE REVIEW

At present, effectively preventing and controlling the pandemic remains the focus of most management scholars. First, in the analysis of the efficiency of pandemic prevention and control, scholars have generally turned to the analysis of the institutional mechanisms and participation factors, such as the public's participation in pandemic prevention and control, the distribution of interests among medical bodies, and the public medical and health system in community areas. All these affect the degree of prevention and control of the pandemic, and problems with pandemic prevention and control in the region should be presented in various states such as social perception (22–24). Second, in terms of prevention and control approaches, scholars believe that media plays important role in the pandemic prevention and control process at the present stage. The current pandemic prevention and control emergency system is slightly weak, the management system is not perfect, and the technical support system is underdeveloped. Only by establishing a multi-center pandemic prevention and control model can the pandemic be truly controlled. The prevention and control of the pandemic should be carried out through effective coordination between regional governments and departments. It is necessary to improve the performance incentive mechanism of local pandemic prevention and control to improve the responsibility and attention of local officials, while actively carrying out audits of the whole process and policy evaluations of pandemic prevention and control. This will give full play to the role of elites in pandemic prevention and control (25–27). Third, there are various research methods for pandemic prevention and control, according to the multiple participants involved. In order to optimize current prevention and control policies and measures, scholars often use collaborative degree models, regression models, social network models, evolutionary game models, and simultaneous equations to analyze the relationship between government, society, enterprise, and the public (28–30). Fourth, scholars actively participate in the exploration of risk management in pandemic prevention and control, and constantly reiterate the importance of risk source identification, emergency resource assessments, monitoring and early warning, advance emergency preparedness, inter-departmental emergency coordination, information disclosure, and public opinion response in pandemic prevention and control. They focus on the whole process of emergency management and network collaboration between departments, and aim to reform the emergency management organization system (31–33). Researchers have conducted in-depth discussions on the mechanisms and paths of pandemic prevention and control, the economic costs of the government, and the issues of governance and supervision, with many research achievements. It is obvious that these studies have not taken into account the medical system costs of pandemic prevention and control, and they lack of an understanding of its importance and necessity. In terms of methods, research on the evolution, perception behavior, and other aspects of the participants in each stage of the pandemic prevention and control node is still lagging behind. Moreover, local government departments tend to ignore medical system costs, influenced by the ideas of "Promotion–Accountability," "Growth First" or "Rational Economic Man." The governments pointed out many times in the prevention and control of COVID-19 that as the situation of pandemic prevention and control is constantly changing, new situations and new problems arise (34). Based on past experience, the spread of the epidemic will have an impact on the normal operation of the economy, and then it will evolve into an important exogenous factor affecting economic growth. Under the impact of the epidemic, the behavior patterns of various entities have undergone drastic adjustments (35). During the protests against and the death of patients in certain sections of Asia, the public first defended their rights and expressed their interests by reasonably expressing their demands. However, due to mishandling by local governments, the low governance capacity of some public officials, and individual local departments who were fighting for themselves and maintaining stability first, the demands of the public could not be effectively resolved. Therefore, scientifically controlling medical system cost consumption in the prevention and control of the pandemic is a major issue that the local government (hereafter referring to government) must face. Therefore, when considering pandemic governance, attention should be paid to the excavation, measurement, and effective use of public medical and health system costs, and as variables for evaluating pandemic governance efficiency. Because attention to these issues will highlight deep-seated and hidden problems associated with pandemic governance, which will substantially enhance the quality and effectiveness of pandemic governance (14). The study contributes to broadening the research perspective of pandemic governance.

However, neither academics nor political circles have established a targeted and systematic evaluation index system and measurement tools for the public medical and health system costs. Most researchers have analyzed the economic cost of pandemic governance from the aspect of "cost-benefit." The study and measurement of the public medical and health system costs of pandemic governance are still in infancy, and there is a lack of field research and empirical analysis in the form of scale development and testing. Therefore, this study mapped public medical and health system cost attrition to a specific field of governmental governance process by combining typical case examples of pandemic governance in China. At the same time, based on the concept and characteristics of public medical and health system costs, this study adopted multi-case rooting theory and fuzzy affiliation evaluation to complete the scientific construction of a public medical and health system cost index system, which turned the public medical and health system cost into an observable variable or outcome variable. In a case study, the public medical and health system cost in S city was measured using the G1/Entropy combination weighting and the fuzzy comprehensive evaluation method, so that the government could perceive the public medical and health system costs in time and introduce or adjust relevant policies and governance programs in a timely and scientific manner.

CONSTRUCTION OF THE MEASUREMENT INDEX SYSTEM

The construction of the public medical and health system costs index system is a complex, systematic project, and the selection of a suitable method is a key part of system construction. It is also important to ensure the scientific basis, operability, and measurement quality of the index system. In addition, it is difficult to quantitatively measure the public medical and health system costs using a single, quantitative, statistical instrument because of the difficulties associated with a quantitative analysis, such as public approval and support. However, since the public medical and health system costs have measurability, they can be assessed using macro data analyses, social surveys, public opinion support and satisfaction tests, public opinion observation, and other measurement tools (36, 37). In view of this, the construction of public medical and health system costs index system is based on the following principles: the first is the principle of operability. It should be guided by relevant theories and existing cases about the public medical and health system costs to ensure that the measurement indicator system is logical and reasonable, that the evaluation is comprehensive and credible, and to make it operational and reliable. The second is the principle of comparability. The selection of the indicator system involves a comparison of different regions, different time periods, and different stages of the indicator system with each other. Therefore, when establishing the indicators, comparisons need to be made between regions or different time periods within the same region so that the indicators are representative and typical. The third is the principle of hierarchy. The public medical and health system costs involve a variety of structural linkages. The intersection of different fields and interdisciplinary synergies mean that the design of the indicator system needs to be coordinated in terms of classification standards and caliber of indicators so that the operational procedures of the evaluation objectives are understood at a general level, the main and secondary indicators should be clarified, the indicators should be interlinked and complementary to each other, and special and qualitative indicators should be scientifically based so that the statistical data are valid (38). The fourth is the principle of combining subjectivity and objectivity. Qualitative or quantitative indicators with clear conclusions should be identified through testing, surveys, and reviews (39), and the indicators should improve the collection and gathering of specific data so that the indicator system can objectively and truly reflect the consumption of public medical and health system costs in order to ensure the validity of the evaluation.

Based on the above principles, this study selected the pandemic governance case in S city that lasted for nearly 2 years, that provided the largest amount of information about the measurement of the public medical and health system costs in order to facilitate field research, data collection and in-depth analysis. The reasons for choosing this case were as follows: (1) the whole pandemic governance event was longitudinal in time. It contained a complete and clear evolution of the public medical and health system costs. (2) It could meet the purpose and requirements of the study. In the case of pandemic governance, the government, enterprises, social organizations (media), the public, and other governance subjects could interact in a hierarchical ladder, and the various elements of the public medical and health system costs can be fully displayed. (3) The selected pandemic governance case included a wide range of recent public opinion and social influence, and the information

TABLE 1 | Sample cases of the public medical and health system costs studies on pandemic governance.

Case sample name	Department	Data collection method	Duration (hour)	Word count
Pandemic governance events in Wuhan City (2020) Screening	Academy of Social Sciences	In-depth interviews	1	1,452
Pandemic governance events in Mudanjiang City (2020) Screening	High School	In-depth interviews	1	1,533
Pandemic governance events in Harbin City (2021) Screening	Research Institute	Symposium	1	1,769
Pandemic governance events in Xi'an City (2021) Screening	Government Departments	Symposium	1.5	2,667
Pandemic governance events in Xingtai City (2020) Screening	College	In-depth interviews	1.5	2,410
Pandemic governance events in Shenyang City (2021) Inspection	College	In-depth interviews	2	3,158
Pandemic governance events in Tonghua City (2021) Inspection	Government Departments	Symposium	2	3,477

TABLE 2 | Research data collection.

Access to information	Source	Main contents	Quantity	Date of publication
Baidu/Google: news, reviews, interviews (D1)	Sina-Blog, Phoenix Finance, S-Government.com, etc.	Development background and the practices of government, nodal events, media commentary, expert views	116	2020.3–2020.7
CNKI, WEB-SCI, SCI-Direct (D2)	Periodicals	Pandemic governance events, etc.	372	2020.11–2021.3
WeChat/Tik Tok/Posting forum/ QICQ group (D3)	Silent Spring public website, S city protection public website, S city's posting bar, Y people in S City and other QICQ groups	Attitudes of local governments and enterprises, official reports, strategies and behaviors, media-related analyses, perception of risks, etc.	719	2020.11–2021.4
Collected through field observation	Villagers provide, observation records	Observation records, research reports, local materials, etc.	15	2020.3, 2021.1

available for investigation and research should cover the issues to be studied as much as possible. The S city was the main sample case, and the seven selected typical cases of pandemic governance were randomly divided into two groups, one of which was used to extract the measurements and the other to test the measurements (**Table 1**).

In order to further develop the measurement index system, field research and data collection were carried out in strict accordance with a set plan and procedures: Step 1—before beginning the field research, a large amount of information was collected and case screening was conducted to identify the objects to be researched. This included using the Internet (search engines, WeChat, Tik-Tok, posting forums, microblogs, QICQ groups, etc.), databases (CNKI, WEB-SCI, SCI-Direct), and the telephone to collect relevant secondary information (see **Table 2**). Step 2—the research plan was formulated and the field research was conducted. In order to prevent some unnecessary factors from interfering with the research, such as interference by the "gatekeeper,"[1] the role of the "insider" was adopted. The participant was observed and allowed to interact with the respondents and interviewers in a participatory manner so that they relaxed their vigilance and lowered their guard, and to ensure that the objectivity and authenticity of

[1] A gatekeeper is a person who has authority over the researched person. The gatekeepers include the head of the pandemic governance unit and government. When arriving in S City in early November, 2020 to try to understand the situation from villagers, we were interfered with by the village committee, and the town government's general government office. It was only after three days and an introduction letter from the Center for Disease Control and Prevention in S City that the investigation could be launched.

TABLE 3 | Basic information about the interview.

Interviewees (Coding)	The form of interview	The length of interview (duration)	Length of the interview (word count)
Villager A1, A2, A3 of S City	Semi structured interview	3 h	3,010
Villager B1, B2, B3 of S City	Semi structured interview	1.5 h	2,671
Citizen F1 of S City	In-depth interview	2 h	2,246
Citizen X1, X2 of S City	Semi structured interview	2 h	2,870
Staff C of S municipal government Staff member W of Center for Disease Control and Prevention	Symposium and interview focus groups	3 h	5,742

TABLE 4 | Example of the open coding process for the public medical and health system costs indicator system (excerpt).

Open coding (conceptualization)	Code (Z_x)	Primary code (ZZ_x)	Original information about the case (Z_x)
Degree of effectiveness of enacting policies and regulations at certain phase of the pandemic governance (including regulation, governance measurements, benefit compensation, etc.) (D_1)	Large number of policies introduced during the period (Z_2)	Regulation, governance measurements, standards, benefit compensation and other policy measurements continue to improve (ZZ_5)	Beijing, Tianjin, and Hebei have issued a "Action plan for the epidemic prevention and control measures" and a "Personnel checking and remote management in the city during pandemic governance and control"; Hebei Province has issued a "Notice on Control and management of external personnel". (Z13)
Degree of closure of telephone/internet complaint cases within the phase of the pandemic governance (D_9)	Inconsistency in the extent of case handling (Z_{18})	Slow processing speed has led to a decline in credibility (ZZ_{43})	"Public complaints about this incident were handled fairly smoothly." (Z_{41}) "We still have blind spots in supervision, and it is often difficult to monitor so it delays the speed of case completion." (Z_{39}) "I think some of the complaints are making a show whether it is the government or the companies." (Z_{43})
Degree of public official accountability (D_{22})	The depth of the degree of punishment for accountability (Z_{45})	The heads of government officials, etc. associated with the misconduct of pandemic governance have been prosecuted, suspended, etc. (ZZ_{105})	"The deputy secretary of the party group in X District of T City was removed from his post and the deputy mayor involved was transferred to the judicial authorities." (Z_{103}) "In our research, we found that enterprise "shut down" behavior was spared by some local governments, which is undoubtedly a distorted view of performance." (Z_{104}) "In this pandemic governance, we implemented administrative accountability for 26 government staff, 12 of whom were removed from their posts." (Z_{101})
Perceived fairness of the interaction (D_{24})	The perceived fairness of government and public response attitude during the process of conflict resolution (Z_{52})	Interpersonal equity refers to the extent to which the public and enterprises are respected and cared for by the government. (ZZ_{121})	"Local governments around Dailian and Shenyang promote the solution of the problem through public announcements of assessments, symposiums, and household visits." (Z_{119}) "I've been kicked around by phone calls and emails." (Z_{56}) "Our governments all convince people to understand the government and invite them to watch the supplies through face-to-face dialogues." (Z_{182}) "The tendency of the government to interact with property owners in a multi-dimensional and proactive manner." (Z_{115})
Public opinion collection and departmental transfer capability (D_{26})	The transmission, interoperability and sharing of information and materials between departments (Z_{56})	Collect and sort out network public opinion, and report the collected information to other departments, so as to formulate relevant collaborative countermeasures (ZZ_{129})	"Government departments are now establishing an early warning mechanism for online public opinion to understand the real-time development of pandemic governance." (Z_{80}) "The local government is controlling online public opinion in a timely manner, and collaborating with the propaganda and Internet information departments to guide and educate on rumors." (Z_{131}) "Exposure in new media and self-media is higher and the local government does not take note of the information." (Z_{128})
…	…	…	…

the research. Step 3—The interviews were recorded, with the consent of the interviewees. Face-to-face in-depth interviews and symposiums, as well as a combination of semi-structured and focus group interviews, were used. This facilitated the organization and coding of the original interview data (**Table 3**), and relevant primary data were collected after interviewing experts, government public officials, and members of social organizations who had studied and participated in, and paid attention to the seven typical cases selected (14 interviews were conducted, and about 16,000 words from interview scripts were compiled) (**Table 1**). Step 4—With the help of ATLAS.ti8 software, the literature and research data were summarized and coded. A system for the public medical and health system costs index system was derived by assigning the "the public medical and health system costs concept" to the data.

Open Coding

With the help of ATLAS.ti8 analysis software, the primary textual information from several typical cases was collected and transcribed to be decomposed. In order to check the authenticity, completeness, and accuracy of the sources of the interview recordings and research data, the data were labeled (zx), formed into primary codes (ZZx), codes (Zx), and finally into open-ended codes (Dx). The same or similar elements existing in the primary information and the primary indicator system were retained, and the more occurrences, the more meaningful the phenomenon represented by the label. A total of 191 primary codes, 87 codes, and 25 open codes were collated and formed, and the relationships between the open codes for the the public medical and health system costs were juxtaposed with each other and their functions, and processes were obtained (see **Table 4** for the open code formation process). After coding, a total of 38 open codes and 10 main axis codes were obtained for the public medical and health system costs measurement index system. An initial system (consisting of 1 primary indicator, 4 secondary indicators, 10 tertiary indicators, and 38 quaternary indicators) was established that was decomposable, independent, comprehensive, and easy to operate.

Associative Codes

The public medical and health system costs indicator system is a multi-level and multi-factor composite structure. Starting with the original concept, this study conceptualized and simplified it by combining previous relevant studies at home and abroad. The system was first divided into two levels: the first level indicator was the total measurement target- public medical and health system costs; and there were four second level indicators, i.e., institutional policy costs, system organizational costs, social perceived costs, and mass behavioral costs. On this basis, the meaning and relationship of each main axis code were reorganized to form four relatively independent core categories and 10 corresponding main axis codes (see **Table 5** for details).

TABLE 5 | Associative codes.

Core categories	Main axis coding
The institutional policy costs (B_1)	Validity of institutional tools (C_1)
	Validity of system implementation (C_2)
	Government credibility and implementation (C_3)
The system organizational costs (B_2)	Competence level of public officials (C_4)
	Integrity level of public officials (C_5)
The social perceptive costs (B_3)	Perception of social equity (C_6)
	Effectiveness of public opinion regulation (C_7)
	Social risk perception (C_8)
The mass behavioral costs (B_4)	Implicit participation behavior of the masses (C_9)
	Explicit participation behavior of the masses (C_{10})

Indicator Amendments

This study followed the scale development procedures of Dunn et al. (40), Marra et al. (41), and others, and combined qualitative analysis methods with scale development testing methods to design questionnaire items, thus ensuring the scientific and objective nature of the assessment. At the same time, the indicators for the public medical and health system costs were revised to solve the problems associated with a large number of indicators, weak generalizability, vague semantics, lack of operability, and an inability to adapt to changing pandemic situations. First, using the expert survey method, this study selected 32 experts, government officials, and members of social organizations who have been engaged in pandemic governance and public crisis management research fields for many years from the regions where typical cases of pandemic governance have occurred. The initial index system was constituted as an expert screening questionnaire for the public medical and health system costs measurement index system. Through a combination of in-depth interviews and expert symposiums, experts and researchers in relevant fields were invited (from universities, research institutions, government agencies, social organizations, and other institutions) to select the indicators they considered the most important for the public medical and health system costs index based on their own academic knowledge and research experience. The aim was to understand their views and opinions and collect constructive opinions. A total of 32 copies of the expert screening questionnaire were returned, of which 30 were valid, and the questionnaire recovery rate and efficiency rate were above 93%. The basic information statistics for the experts are shown in **Table 6(A)**. After distributing the questionnaires to collect the survey data, this study undertook a redundancy analysis of the information given by the experts, refined the summary, and used fuzzy statistical analysis to eliminate the measurement items with low affiliations to finally determine the formal measurement index system.

Given that the public medical and health system costs are fuzzy concept, the public medical and health system costs indicator system are also considered to be a fuzzy set: $\{Y\}$ was defined as the indicator set, i.e., each indicator in the indicator system was considered to be an element in the set, and then

TABLE 6 | Expert screening results and memberships for each measurement.

(A) Expert information statistics

Project	Category	Proportion
Gender of the expert	Male	63.3
	Female	36.7
Age	26–29 years old	10
	30–39 years old	20
	40–49 years old	43.3
	Over 50 years old	26.7
Education level	Undergraduate	16.7
	Master	40
	Doctorate	43.3
Work unit	Government agencies	23.3
	Research Institutes	16.7
	Universities	50
	Social organizations and other institutions	10
Title	Primary Title	0
	Intermediate Title	26.7
	Deputy Senior Title	33.3
	Senior title	40

(B) Selection results and membership of experts

Four levels of indicators, number of expert tick marks, membership values, retention (yes/no) for the public medical and health system costs	Number of expert selections	Membership function value	Reserved (yes/no)
Degree of effectiveness of policies and regulations enacted during the period (including regulation, governance measures, benefit compensation, etc.) (D_1)	14	0.47	N
Degree of effectiveness of existing policies and regulations (including regulation, governance measurements, benefit compensation, etc.) (D_2)	29	0.97	Y
Scientific basis and legitimacy of pandemic governance policy tools (including the degree of expert validation, assessment system, etc.) (D_3)	29	0.97	Y
Completeness of the emergency prevention and control system (mechanism) (D_4)	27	0.9	Y
Consistency of system policy and government implementation (D_5)	28	0.93	Y
Degree of fulfillment and delivery of system policies (D_6)	28	0.93	Y
Degree of administrative punishment at this level (including interviews, warnings, fines, etc.) (D_7)	25	0.83	Y
Degree of completion of administrative reconsideration cases received within the period (D_8)	16	0.53	N
Degree of completion of telephone/internet complaint cases within the stage (D_9)	26	0.8	Y
Government authority (including regulation, information response, etc.) (D_{10})	27	0.9	Y
Image of the government (D_{11})	17	0.57	N
Reasonable degree of institutional setup (D_{12})	15	0.5	N
Administrative effectiveness (including departmental governance efficiency, degree of interdepartmental synergy, etc.) (D_{13})	26	0.86	Y
Level of pandemic literacy (D_{14})	15	0.5	N
Professional technology and risk assessment capacity (D_{15})	28	0.93	Y
Pandemic risk emergency response capacity (including research and evaluation capabilities, information dissemination channels, mobilization and decision-making, etc.) (D_{16})	30	1	Y
Ability to repair the relationship between the government and the people (communication ability, etc.) (D_{17})	27	0.9	Y

(Continued)

TABLE 6 | Continued

Four levels of indicators, number of expert tick marks, membership values, retention (yes/no) for the public medical and health system costs	Number of expert selections	Membership function value	Reserved (yes/no)
Degree of integrity and diligence of public officials (D_{18})	28	0.93	Y
Degree of pandemic control enforcement regulation (D_{19})	25	0.83	Y
Number of officials involved in corruption as a percentage of administrative personnel (D_{20})	14	0.47	N
Degree of accountability of public officials (D_{21})	16	0.53	N
Perceived procedural fairness (transparency, etc.) (D_{22})	25	0.83	Y
Perceived distributive justice (D_{23})	27	0.9	Y
Perceived interactional fairness (D_{24})	16	0.53	N
Sensitivity and responsiveness of public opinion (D_{25})	17	0.57	N
Public opinion collection and departmental transmission ability (D_{26})	27	0.9	Y
Ability to guide public opinion (D_{27})	29	0.97	Y
Ability to promote and educate pandemic governance theory (D_{28})	16	0.53	N
Physiological risk perception (D_{29})	29	0.97	Y
Property risk perception (D_{30})	17	0.57	N
Psychological risk perception (D_{31})	29	0.97	Y
Public satisfaction (D_{32})	30	1	Y
Level of political trust (D_{33})	27	0.9	Y
Level of political identification (D_{34})	15	0.5	N
Level of public participation in pandemic governance within the stage (D_{35})	15	0.5	N
Level of public participation in symposiums and hearings within the stage (D_{36})	25	0.83	Y
Degree of media access by people within the stage (the number of clicks on governmental platform visits, the number of likes, retweets, and comments on articles related to microblogs, Tik-Tok, and WeChat public numbers, etc.) (D_{37})	27	0.9	Y
Negative behaviors generated by people (smashing, blocking, fighting, rumor-mongering, etc.) (D_{38})	28	0.93	Y

the expert survey method was used to conduct the indicator affiliation analysis and calculate the affiliation of 38 indicators of the public medical and health system costs. Based on this, we were able to determine whether to keep them in the public medical and health system costs index system. Assuming that the total number of expert confirmations for the i-th. indicator Y_i is Z', i.e., a total of Z_i experts confirm Y_i as an important evaluation indicator for assessing the public medical and health system costs, and the total number of people measured is 30, then the affiliation degree of the public medical and health system costs indicator is:

$$R_i = \frac{Z_i}{30}(i = 1, 2, ..., 30) \tag{1}$$

Whether the measurement index Z_i is taken or rejected depends on whether its membership, R_i is greater than or less than the critical membership. If it was the former, the measurement index was retained; if was the latter, it was deleted when critical membership = the critical value of expert selection times $Z/30$. Therefore, the critical value of expert confirmation times Z ($\alpha = 0.01$) is:

$$Z = \mu + \frac{S}{\sqrt{Z'}} t_{0.01} = 23.4 + \frac{5.77}{\sqrt{1140}} \times 2.368 = 23.8 \tag{2}$$

In Formula 2, S denotes the standard deviation of the number of expert confirmations, μ denotes the expected value of the number of expert confirmations, Z'denotes the total number of expert confirmations, and $t_{0.01}$ denotes the T-test value at a significance level of $\alpha = 0.01$. An analysis of the data calculation showed that the critical affiliation was 79.4% when the critical value of the number of expert confirmations was $Z = 23.8$. Therefore, when the affiliation degree ($\alpha = 0.01$) of an indicator was <79.4%, then the indicates was not statistically significantly different within the public medical and health system costs indicator system and was removed. Among the 38 indicators measuring the public medical and health system costs in the thesis, 13 indicators had an affiliation degree <79.4%, as detailed in **Table 6(B)**. Thirteen indicators were removed from the 38 indicators in the second round of the indicator system construction process and 25 indicators were retained.

After expert testing and revision, this study finally determined the public medical and health system costs as a four-level index system with 40 indicators, of which the first-level indicator was the public medical and health system costs and the second-level indicator contained four points. Each secondary indicator had corresponding tertiary and quaternary indicators, which consisted of the original 10 tertiary indicators and 25 quaternary indicators identified by the redundancy analysis. In addition, the presentation of some of the level 4 indicators was corrected based on the results of the in-depth interviews (see **Table 7**).

Confidence Validity Testing and Saturation Testing of the Coding

The Scott's P_i index was chosen as the reliability test when coding the nature of the public medical and

TABLE 7 | The public medical and health system costs indicator system after amendments.

Primary indicators	Secondary indicators	Tertiary indicators	Quaternary indicators
The public medical and health system costs	Institutional policy costs (B_1)	Validity of institutional tools (C_1)	Degree of effectiveness of policies and regulations enacted during the period (including regulation, governance measures, benefit compensation, etc.) (D_1)
			Scientific basis and legitimacy of pandemic governance policy tools (including the degree of expert validation, assessment system, etc.) (D_2)
			Completeness of the emergency prevention and control system (mechanism) (D_3)
		Validity of system implementation (C_2)	Consistency of system policy and government implementation (D_4)
			Degree of fulfillment and delivery of system policies (including the implementation of norms) (D_5)
			Degree of administrative punishment at this level (including interviews, warnings, fines, etc.) (D_6)
			Degree of completion of telephone/internet complaint cases during the period (supervision, information response, etc.) (D_7)
	System organizational costs (B_2)	Government credibility and implementation (C_3)	Government authority (including regulation, information response, etc.) (D_8)
			Degree of interdepartmental synergy (D_9)
		Competence level of public officials (C_4)	Expertise and ability to assess risks (D_{10})
			Emergency response capacity of pandemic risks (research and evaluation capacity, information release channels, mobilization and decision making, etc.) (D_{11})
			Ability to repair the relationship between the government and the people (communication ability, etc.) (D_{12})
		Integrity level of public officials (C_5)	Degree of integrity of public officials (D_{13})
			Degree of diligence of public officials (D_{14})
	Socially perceived costs (B_3)	Perception of social equity (C_6)	Perceived procedural fairness (transparency, etc.) (D_{15})
			Perceived fairness of distribution (D_{16})
		Effectiveness of public opinion regulation (C_7)	Ability of public opinion collection and departmental transmission (D_{17})
			Ability to guide public opinion (D_{18})
		Social risk perception (C_8)	Physiological risk perception (D_{19})
			Psychological risk perception (D_{20})
	Mass behavioral costs (B_4)	Implicit participation behavior of the masses (C_9)	Public satisfaction (D_{21})
			Political trust level (D_{22})
		Explicit participation behavior of the masses (C_{10})	Intensity of public participation in symposiums and hearings during the stage (D_{23})
			Degree of media access by people within the stage (the number of clicks on government platform visits, the number of likes, retweets and comments on articles related to microblogs, Shake, and WeChat public numbers, etc.) (D_{24})
			Negative behaviors generated by people (smashing, blocking, fighting, rumor-mongering, etc.) (D_{25})

TABLE 8 | Degree of consistency of the coding.

Category	Open coding	Axial coding	Selective coding	Total
Total number of codes	38	10	1	49
Number of consistency codes	31	10	1	42
X%	81.6	100	100	85.7

TABLE 9 | Results of coding saturation analysis.

Category	A and B	B and C	A and C
Number of codes that fully agree with each other	83	86	81
Average mutual agreement degree	0.83	0.86	0.81

health system costs. The formula for calculation is as follows:

$$Pi = \frac{X\% - Y\%}{1 - Y\%} \quad (3)$$

X = The number of analysis columns with identical coding results by two coders. Y = Expected value for consistency of coding results. The results are shown in **Table 8**.

Scott's P_i was calculated to be 0.857 (generally, a value above 0.8 indicates good reliability), and therefore the coding part of the public medical and health system costs analysis was reliable. In order to ensure the validity of the coding and to further test the theoretical saturation of the public medical and health system costs measurement index system, the same or similar pandemic governance cases in China were selected for validation. In this paper, following the above standardized open coding procedures, three experts were selected to conduct saturation reliability analysis on the two groups of verification cases in the open coding process. Expert A analyzed a total of 176 original materials and codes in the two sets of cases, while Expert B and Expert C analyzed the same 100 source materials and codes for both sets of cases. One hundred source materials and codes analyzed by the three experts were taken as samples for reliability saturation analysis, and the results of the reliability saturation analysis are shown in **Table 9**.

The average agreement degree of the three was $K \approx 0.833$, and it was obtained that $R \approx 0.85$ through the reliability calculation formula, so the reliability of the coding was high. The saturation test results showed that: The categories in the index system had been edited and enriched, and no new categories or analogous relationships were found, which meant that the system had passed the coding validity test and reached saturation. Thus, the index system for the public medical and health system costs constructed in this study was scientific and reasonable.

APPLICATION ANALYSIS OF THE MEASUREMENT INDEX SYSTEM

Selection of Measurement Methods

The above analysis revealed that the public medical and health system costs index system was an abstract system and its measurement highlighted the problem of rational social choice and group decision making. The process of social choice and group decision making is based on how group members with common interests, different information, and different decision-making abilities join together to make the best decision (42). Whether it is through participation behavior or public activities, many different social choices and group decisions can play an extremely important role. Therefore, reasonable social choices and group decisions will directly affect the reduction in the public medical and health system costs consumption and the improvement in pandemic governance efficiency. In this kind of social choice and group decision process, the attribute values of the measured objects are mostly expressed in the form of fuzzy numbers or interval gray numbers. However, obtaining accurate and reasonable information about the true preferences and attributes of group decision making is often difficult because group utility functions are determined by well-defined individual utility functions (43), which means that assembling individual utility functions into group utility functions is a key aspect of the measurement process. The development of stochastic nonlinear utility and fuzzy decision theory has meant that most studies have tended to use fuzzy mathematical models to "synthesize" multiple evaluation index values into a holistic comprehensive evaluation value, and then obtain group preference relationships and group decision results. The attribute weights reflect the degree of importance that the assessor places on the assessment target, the degree of variation in the values of the assessment indicators, and the degree of reliability of the attribute values for the assessment target (44). Many methods have been used to obtain attribute weights, such as hierarchical analysis, the entropy method, etc. The multi-objective decision problems of social choice and group decision making can be transformed into single-objective decision problems through the calculation of weights (45). Attribute weights are also influenced by subjective and objective factors, and reasonable weight assignment methods are needed to improve the accuracy of weight assignment. The fuzzy comprehensive evaluation method refers to the use of multiple indicators based on a fuzzy set with hierarchical rows to make a comprehensive evaluation and classification of the subordinate rank status and change interval of the evaluated object. This method highlights the fuzzy nature of the evaluation criteria and influencing factors, and it can also combine qualitative and quantitative factors in the evaluation. This improves the accuracy and of the evaluation number, which means that evaluation conclusion is credible and thus it is more effective in evaluating complex problems with multiple factors and levels (46, 47). Furthermore, the public medical and health system costs are dynamic and comprehensive fuzzy concept, and are affiliation vector about multi-level rubrics where the rubric levels are grouped isometric ally.

Therefore, this study took the multi-attribute decision problem with a fuzzy number of attribute values as the starting point and used the G1 method to determine the subjective weight coefficients of each indicator of the public medical and health system costs. At the same time, the entropy weight method was used to determine the objective weight coefficients of each indicator of the public medical and health system costs. The level values of the public medical and health system costs of pandemic problems and the optimal combined G1/entropy weights of its indicators were determined by the combination method of subjective and objective assignments. Then, the descending semi-trapezoidal distribution method was selected based on the evaluation level of each indicator, the affiliation distribution function was calculated, and the fuzzy transformation principle was used to determine the value of the public medical and health system costs. This methodology meant that it was possible to clearly and reliably conclude the group decision made by some individuals and judge the real attitudes and choices of actors about pandemic problem coping strategies. This meant that the measurement of the public medical and health system costs had wider non-contingency, applicability and practicality.

Measurement Design and Data Acquisition

The questionnaire about the public medical and health system costs are designed around the understanding ability of villagers and citizens based on the 25 four-level indicators of the index. The questionnaire contained nine items of basic information about the respondents and 25 items that were scored on a seven-point Likert scale. The target of the scale was still the pandemic prevention and control event in S City, and it was gradually improved by consulting experts from universities and research institutes in the Beijing-Tianjin-Hebei region, local people, surrounding village cadres, and government authorities, etc. The objective weights of the four levels of indicators were calculated from the questionnaire and the public medical and health system costs to the government of S City when managing the pandemic were measured. This study questionnaire survey was conducted in two phases according to the development of events, and was carried out in parallel with interviews and resident research. The survey was conducted using the random distribution method and face-to-face interviews. The survey and processing of the first phase of the questionnaire took place between December 25, 2020 and January 11, 2021. The second phase of the survey and processing of the questionnaire took place between December 1, 2021 and December 21, 2021. A total of 400 questionnaires were distributed to meet the sampling requirements, of which 377 questionnaires were collected, with a recovery rate of 94.2%. There were 309 valid questionnaires, which was an effective rate of 82%.

Given the duplication of measurement processes in the two questionnaire phases, the first phase of the research questionnaire and data were selected to analyze the process of assigning and measuring the public medical and health system costs. Prior to each phase of the formal survey, a pretest was conducted to ask whether the subjects could clearly understand and easily respond. Then, the questionnaire was revised in several rounds until it showed good internal validity. The Cronbach's α values for the four measurements of the public medical and health system costs of the questionnaire study were 0.728, 0.726, 0.714, and 0.702, which showed that the measurements had excellent reliability levels. The scale was purified using the Corrected Item-Total Correlation (CITC). Question items with a CITC value of 0.5 or below were considered less relevant to the overall results. If Cronbach's α increased significantly when these question items were deleted, it was decided that these questions should be deleted to achieve scale purification. The results showed that all 25 question items passed the test, that is, the Cronbach's α coefficient of each indicator was greater than the critical value of 0.6, which meant they were highly reliable and there was no need to delete any question items. The validity test of the questionnaire used in the first questionnaire phase analysis used the Kaiser-Meyer-Olkin (KMO) measurement and Bartlett's sphericity test. After testing, the KMO values of four of the indicators were >0.6, and thus the questionnaire had significant structural validity. The Bartlett's test of significance was 0.000, and the significance expression met the requirements, so the questionnaire had high validity and could be used for objective weighting and the measurement of the public medical and health system costs.

Combination of Subjective and Objective Empowerment and Fuzzy Measurements

G1 Method to Determine the Weights of the Measurement Indicators

The G1 method improves on the AHP (Analytic Hierarchy Process) method by getting rid of the constraint that decision makers must construct a judgment matrix when judging the scheme, avoids the disadvantage that it is difficult to meet the consistency requirements of the AHP method, and fundamentally solves the consistency problem of individual judgment. Furthermore, the G1 method does not need a consistency test. This method is especially suitable for weighting large scale index systems with many factors. Therefore, the G1 method was selected for the subjective weighting.

In this study, seven experts who have been engaged in the research fields of pandemic governance and public crisis management for many years were invited. After judging the relationship of each indicator to the public medical and health system costs, their importance was assigned as follows:

Let $x_1, x_2, x_3, \ldots, x_m$ $(m \geq 2)$ be m extremely large indicators that have undergone uniformization and non-dimensionalization of indicator types.

Definition 1: If the importance of index x_i relative to a certain evaluation criterion (or target) is not inferior to x_j, it is recorded as $x_i \geq x_j$ (the symbol $\geq$ indicates that it is not an inferior relationship).

Definition 2: If index $x_1, x_2, x_3, \ldots, x_m$ has a relationship with an evaluation criterion (or objective):

$$x_i \geq x_j \geq \cdots x_k (i, j, \ldots, k = 1, 2, \ldots m) \tag{4}$$

then it is said that the evaluation indexes $x_1, x_2, x_3, \ldots, x_m$ have established an order relationship according to "$\geq$".

TABLE 10 | The scale.

r_k	Definition
1.0	Indicator x_{k-1} is as important as indicator x_k
1.2	Indicator x_{k-1} is slightly more important than indicator x_k
1.4	Indicator x_{k-1} is obviously more important than indicator x_k
1.6	Indicator x_{k-1} is more important than indicator x_k
1.8	Indicator x_{k-1} is extremely more important than indicator x_k

For the evaluation index set $\{x_1, x_2, x_3, \ldots, x_m\}$, the order relationship can be established according to the following steps:

Select the most important or least important of the m indicators and mark it as x_i;

Select the most important or least important indicator among the remaining *m-1* indicators and mark it as x_j;

Select the most important or least important indicator among the remaining *m-(k-1)* indicators and mark it as x_n; Mark the remaining indicator as x_k.

After determining the only order relationship, the next step is to determine the importance of adjacent indicators.

Under the selected scale, the rational judgment of the selected experts on the importance ratio w_{k-1}/w_k between adjacent indexes x_{k-1} and x_k is derived as follows:

$$w_{k-1}/w_k = r_k(k = m, m-1, m-2, \ldots, 3, 2) \tag{5}$$

When the number of indicators is large, the most minor indicator $r_m = 1$ can be used and the r_k value can be derived from **Table 10**.

The information and data filled in by the experts can then be combined to calculate the indicator weights layer by layer using the G1 method.

If the expert gives a rational assignment of r_k, the weight w_j^g is:

$$w_j^g = (1 + \sum_{k=2}^{m} \prod_{i=k}^{m} r_i)^{-1} \tag{6}$$

$$w_{k-1} = r_k w_k(k = m, m-1, m-2, \ldots, 3, 2) \tag{7}$$

Finally, the single-tier subjective weights and comprehensive weights of 1 primary indicator, 4 secondary indicators, 10 tertiary indicators and 25 quaternary indicators were completed after collating the assignment results, as shown in **Table 11**.

Determination of the Weights of the Measurement Indicators by the Entropy Method

The importance of the 25 question items is calculated in strict accordance with the steps of the entropy value method for assigning weights, and the objective weights of the public medical and health system costs (four levels of indicators) were derived. Since the objective weighting of the public medical and health system costs measurement index used the questionnaire survey data, there was no need for dimensionless processing of the data, and the calculation formula is as follows.

Index information entropy:

$$e_j = -k \sum_{i=1}^{n} Y_{ij}' \ln Y_{ij}', j = 1, 2, 3 \ldots, m \tag{8}$$

Index redundancy:

$$d_j = 1 - e_j, j = 1, 2, 3, \ldots, m \tag{9}$$

Index entropy:

$$w_j^s = d_j / \sum_{j=1}^{m} d_j, j = 1, 2, 3, \ldots, m \tag{10}$$

where: e_j is the information entropy $Y_{ij}' = Y_{ij}/\sum_{i=1}^{n} Y_{ij}$ of index j; d_j is the redundancy of index j; w_j^s is the entropy weight of index j; m is the number of indicators, n is the number of questionnaires, and k is the adjustment coefficient ($k = 1/\ln n$).

The calculation results are shown in **Table 11**.

Portfolio Weights

The key problem of combined weighting is how to determine the weight distributions of the two methods. An extensive literature review found that most researchers had used the method of subjective and objective average weighting with the minimum sum of squared deviations as the objective function to calculate the combined weight. Furthermore, this study calculated the public medical and health system costs on the basis of the identified indicator system, without the need for indicator rejection and without the need to reflect the differences between expert knowledge and experience, and the objective data. The results suggested that the multiplicative synthetic normalization method with the linear weighted combination method was suitable for calculating the combined weighting.

Suppose w_j^z is the j-th index weight obtained by a linear combination of the two weighting methods, that is:

$$w_j^z = \lambda w_j^g + (1 - \lambda) w_j^s \tag{11}$$

where λ is the proportion of the index weight determined by the G1 method in the combined weight. The objective function is constructed by minimizing the deviation between the index weight determined by the G1 method and the combined weight, and the square sum of the deviation between the index weight determined by entropy method and the combined weight is:

$$\min z = \sum_{j=1}^{n} [(w_j^z - w_j^g)^2 + (w_j^z - w_j^s)^2] \tag{12}$$

TABLE 11 | Combined weights of the indicators for measuring the public medical and health system costs in the first phase of the questionnaire process.

Primary Indicator	Secondary Indicator Single-tier weighting	Tertiary indicators Single-tier weighting	Quaternary indicators Single-tier weighting	Composite Subjective weighting W_g^j	Questionnaire Objective weighting W_s^j	Portfolio Weighting W_z^j
(A)1	(B_1) 0.2362	(C_1) 0.4167	(D_1) 0.4248	0.0418	0.0409	0.0414
			(D_2) 0.3539	0.0348	0.0400	0.0374
			(D_3) 0.2213	0.0218	0.0382	0.0300
		(C_2) 0.5833	(D_4) 0.2049	0.0282	0.0351	0.0317
			(D_5) 0.3443	0.0474	0.0350	0.0412
			(D_6) 0.2459	0.0339	0.0417	0.0378
			(D_7) 0.2049	0.0282	0.0359	0.0321
	(B_2) 0.2362	(C_3) 0.2778	(D_8) 0.3846	0.0252	0.0408	0.0330
			(D_9) 0.6154	0.0404	0.0382	0.0393
		(C_4) 0.4444	(D_{10}) 0.2212	0.0232	0.0396	0.0314
			(D_{11}) 0.4248	0.0446	0.0376	0.0411
			(D_{12}) 0.3540	0.0372	0.0387	0.0379
		(C_5) 0.2778	(D_{13}) 0.5000	0.0328	0.0395	0.0362
			(D_{14}) 0.5000	0.0328	0.0416	0.0372
	(B_3) 0.1969	(C_6) 0.3017	(D_{15}) 0.4167	0.0248	0.0448	0.0348
			(D_{16}) 0.5833	0.0347	0.0403	0.0375
		(C_7) 0.2155	(D_{17}) 0.6429	0.0273	0.0407	0.0340
			(D_{18}) 0.3571	0.0152	0.0383	0.0267
		(C_8) 0.4828	(D_{19}) 0.6154	0.0585	0.0387	0.0486
			(D_{20}) 0.3846	0.0366	0.0368	0.0367
	(B_4) 0.3307	(C_9) 0.4167	(D_{21}) 0.5455	0.0752	0.0391	0.0571
			(D_{22}) 0.4545	0.0626	0.0366	0.0496
		(C_{10}) 0.5833	(D_{23}) 0.2033	0.0392	0.0416	0.0404
			(D_{24}) 0.2846	0.0549	0.0494	0.0521
			(D_{25}) 0.5121	0.0988	0.0508	0.0748

The calculation results are retained to four decimal places.

From Formula (12), we get:

$$\min z = \sum_{j=1}^{n} [\lambda w_j^g + (1-\lambda) w_j^s - w_j^g]^2 + [\lambda w_j^g + (1-\lambda) w_j^s - w_j^s]^2 \tag{13}$$

Then, find the derivative of Formula (13) with respect to λ and set the first-order derivative to 0 to obtain $\lambda = 0.5$. Substituting $\lambda = 0.5$ into Formula (11) allows, the weight value after the combined weighting to be can be obtained as follows:

$$w_j^z = 0.5 w_j^g + 0.5 w_j^s \tag{14}$$

The subjective and objective weights of the indicators for measuring the public medical and health system costs are unified by combining the objective weights obtained by the entropy method with the subjective comprehensive weights for each indicator obtained by the G1 method according to the above formula. These weights can then be used to calculate the combined weight of each indicator. The calculation results are shown in **Table 11**.

The overall weight rankings of the indicators for the public medical and health system costs in **Table 11** show that although the G1 method and entropy method had different emphases in the calculation and analysis of indicator weights, there was still a high degree of consistency in the subjective ranking, objective ranking, and overall ranking results for more than half of the indicators. This result also indicates, to a certain extent, that the combined weighting method based on the G1 method and entropy method was scientific and applicable.

Fuzzy Integrated Measurement

Step 1. After calculating the combined weights of the public medical and health system costs indicators, the final measurement analysis was carried out according to the above fuzzy comprehensive evaluation method. The data were chosen from the questionnaire data for the area surrounding the studied case in the first phase of the questionnaire process.

Establish the set of evaluation factors U. Public medical and health system costs: U = {U1, U2, U3, U4}. Institutional policy costs: U1 = {U11, U12}. System organizational costs: U2 = {U21, U22, U23}. Socially perceived costs: U3 = {U31, U32, U33}. Mass behavioral costs: U4 = {U41, U42}. Validity of institutional tools: U11 = {U111, U112, U113}. Validity of system implementation: U12 = {U121, U122, U123, U124}. Government credibility and implementation: U21 = {U211, U212}. Competence level of public officials: U22 = {U221, U222, U223}. Integrity level of public officials: U23 = {U231, U232}. Perceived social equity: U31 = {U311, U312}. Effectiveness of public opinion regulation: U32 = {U321, U322}. Social risk perception: U33 = {U331, U332}. Implicit participation behavior of the masses: U41 = {U411, U412}. Explicit participation behavior of the masses: U42 = {U421, U422, U423}.

Step 2. The set of comments (V) were determined where V= {strongly agree, agree, relatively agree, average, relatively disagree, disagree, strongly disagree} = {7, 6, 5, 4, 3, 2, 1} respectively.

Step 3. The factor weights and sub-factor weights were then determined. Here the weight values (values were calculated to three decimal places) after the combination assignment in the previous subsection were used.

A = (0.285, 0.256, 0.218, 0.274). A1 = (0.109, 0.143). A2 = (0.072, 0.110, 0.073). A3 = (0.072, 0.061, 0.085). A4 = (0.107, 0.167). A11 = (0.041, 0.037, 0.030). A12 = (0.032, 0.041, 0.038, 0.032). A21 = (0.033, 0.039). A22 = (0.031, 0.041, 0.038). A23 = (0.036, 0.037). A31 = (0.035, 0.037). A32 = (0.034, 0.027). A33 = (0.049, 0.037). A41 = (0.057, 0.050). A42 = (0.040, 0.052, 0.075).

Step 4. The fuzzy comprehensive evaluation matrix calculation for the sub-factor set was performed, where:

$$R_{11}=\begin{Bmatrix} R_{111} \\ R_{112} \\ R_{113} \end{Bmatrix} = \begin{Bmatrix} r_{1111}...r_{1117} \\ r_{1121}...r_{1127} \\ r_{1131}...r_{1137} \end{Bmatrix}$$

......

$$R_{42}=\begin{Bmatrix} R_{421} \\ R_{422} \\ R_{423} \end{Bmatrix} = \begin{Bmatrix} r_{4211}...r_{4217} \\ r_{4221}...r_{4227} \\ r_{4231}...r_{4237} \end{Bmatrix} \tag{15}$$

$$B_{11} = A_{11} \cdot R_{11}$$

......

$$B_{42} = A_{42} \cdot R_{42} \tag{16}$$

$$B = B_{11} + ... + B_{42} \tag{17}$$

Step 5. The fuzzy comprehensive evaluation result vector was synthesized. The fuzzy comprehensive evaluation result vector was obtained after inputting the measurement results for all the public medical and health system costs indicators into the judgment matrix as follows:

$$\begin{aligned} B &= B_{11} + ... + B_{42} \\ &= (0.050, 0.126, 0.204, 0.296, 0.156, 0.123, 0.044) \end{aligned} \tag{18}$$

According to the principle of maximum affiliation, the evaluation set for the public medical and health system costs indicators was considered to be "average," and the feature vector was 0.296.

Step 6. A comprehensive measurement analysis of the result vector for the fuzzy comprehensive evaluation was undertaken. The comprehensive score for the public medical and health system costs measurements was obtained from $\theta = B \times D^T = 4.071$. That is, in the pandemic governance at the S City, the measured value for the public medical and health system costs produced by the first stage of the pandemic governance was 4.071.

Given the different attributes and magnitudes of the public medical and health system costs indicators in the two governance stages, the objective questionnaires used to measure the two stages were different. Furthermore, the resulting objective factor weights and fuzzy evaluation composite values were also different. Although the assignment of experts allows for comprehensive judgment and subjectivity, and the same weight is given to both stages, the combination of the objective questionnaire data conducted simultaneously with the two governance stages still resulted in a more reasonable and accurate calculation of the public medical and health system costs indicator weights for each stage. The above calculation process gives a value of 4.133 for the public medical and health system costs indicators during the second governance stage in S City. In the survey, the scoring items in the seven-point Likert scale were used and were scored based on the respondents' agreement with the question items in descending order. When the public medical and health system costs measurement was <4.071, the public medical and health system costs and benefit to the pandemic governance are in a balanced state, and the local pandemic governance is in a safe and stable period. However, when the public medical and health system costs measurement is >4.071, then the public medical and health system costs are viciously consumed and the local pandemic governance system has entered a dangerous period. The government needs to focus on the public medical and health system costs.

CONCLUSIONS AND POLICY IMPLICATIONS

Main Conclusions

After measuring the combined weights of the public medical and health system costs, it can be concluded that the weights of the measured indicators evolved according to the different temporal and spatial states of the measured objects and pandemic governance events, and the importance of each indicator in each stage to the public medical and health system costs varied. Among them, mass behavioral costs and the five categories that included fourth-level indicators had the greatest weight among all the indicators and had a greater impact on the public medical and health system costs results. They are also the core elements affecting the public medical and health system costs consumption. And three other the public medical and health system costs (institutional policy, system organizational, and social perception) that have a more balanced degree of influence. In the four-level indicator system, the weight of "negative behaviors generated by people" is the largest among the stages, and "public satisfaction" is the second largest factor affecting the public medical and health system costs, so the government must focus on the analysis public interest of pandemic governance. The other four levels of indicators significantly fluctuated in their weights at each stage depending on the nature of the event. In addition, when the reliability and validity of the questionnaire were tested, it was found that the scores for respondent evaluation of institutional policy and system organizational costs caused to pandemic governance were more consistent, and the values of these two indicators in the questionnaire were high in the reliability and validity tests. The variability of the respondent evaluation scores on the social perception costs of pandemic problems and the behavioral cost of the masses indicators were greater than for the other indicators, which makes the values of these two indicators in the questionnaire low in the reliability and validity tests. These two situations are consistent with the assumptions of the pre-survey and the actual situation highlighted by the field research.

The public medical and health system costs of the pandemic governance in S City were already evident during the first stage of the COVID-19 pandemic governance event. However, because the local government did not pay much attention to it due to reasons such as "employment rates," "local stability and security" and "increase in local GDP," the public medical and health system costs evolved during the first stage. In the first stage, local governments failed to provide timely guidance, treatment, and systems to address the problems and public opinion information reflected by the public. At the same time, the public medical and health system costs in the first stage was 4.071, which meant that The public medical and health system costs significantly increased during this stage and was at the critical point of the "cost-benefit" equilibrium for the government to manage pandemic problems. In this context, if the local government does not pay attention to the problem, it will inevitably evolve into the second stage. The second stage witnessed negative public behavior, and negative public psychology began to expand and spread rapidly. However, the failure of local government to carry out effective public emergency responses and governance led to the continuous expansion of the public medical and health system costs consumption. At this point, the measured value for The public medical and health system cost was 4.133, suggesting that the S City government should introduce and adopt timely governance policies and invest more active governance efforts to control the continued rise in the public medical and health system costs depletion. This index system shows that the measurement results have high consistency with the actual event evolution results, and it also proves that the measurement index system and measurement method for ascertaining the public medical and health system costs constructed in this study are practical. Therefore, when practicing local pandemic governance, the government can use the index system and measurement method to measure the size of the public medical and health system costs in the region and use it as an important basis for measuring the performance of pandemic governance.

The risk society theory is combined with the "cost-utility" theory in this paper. In line with the case analysis and cost measurement, it is concluded that local governments often take advantage of system resources for rent-seeking and result in high system costs in the process of pandemic prevention and control. Coupled with the system costs inflation caused by the wrong decision-making of some local governments and the underestimate of virus risk, the "cost-benefit" imbalance in the supply of public goods in the process of pandemic prevention and control is caused. The local governments as the "Rational Economic Man" that take the pursuit of maximizing their own interests as their own behavioral motivation. After that, the best scheme is selected by them to realize their own interests. In this case, the weaker collinearity between the regional pandemic control benefits and the overall level of local governance is presented. Since the externalities of the pandemic control are shown, the public interest is usually composed of political, social, economic and other multidimensional elements, the positive externalities are far from enough for local governments to guarantee both economic efficiency and social equity. The local governments will deviate from the public's agency goals of pandemic control to a certain extent due to the lack of reasonable constraints and supervision, so the certain risks will be caused. In view of it, the transmission nature and critical connection between cost-utility theory and risk society theory are proved in this thesis. Therefore, the asymmetry in the allocation of their own interests and the interests of other subjects such as the public should be focused on by the local governments, the payment cost of the client in the pandemic control should be paid attention to, the public choice theory should be introduced. In short, a perfect cost-benefit indicator management system and an efficient citizen participation mechanism should be set up, the system should be rationally formulated, and the participation channels of other governance subjects should be broadened, so various "transaction costs" in the process of pandemic governance can be reduced. In this thesis, the crucial role of the public choice theory in pandemic prevention and control is demonstrated. The costs of public health and medical system are taken as one of the variables to evaluate the efficiency of local government pandemic governance, so the research on pandemic governance will be more systematic and pertinent.

Policy Implications

Local governments should establish the public medical and health system costs awareness and adopt appropriate assessment and enforcement efforts. And local governments should establish a the public medical and health system costs control mechanism and an automatic identification and monitoring mechanism, make good use of the emotional buffer in the virtual space of the network, and pay attention to early warnings during each stage of pandemic governance in order to issue and adopt governance policies in a timely manner to control the consumption of the public medical and health system costs. At the same time, local governments often form their own preferences based on local economic benefits, taxation, and governance costs to determine the intensity of pandemic governance policies. When economic benefits are consistent with local pandemic governance preferences, local governments are prompted to implement governance policies while ignoring the public medical and health system costs. When the two preferences are inconsistent, local governments often adopt incomplete implementation and avoidance of responsibility for scientific pandemic governance. However, the public medical and health system resources held by governance active subjects when managing the pandemic are limited. Therefore, this approach will increase the consumption of the public medical and health system costs, will have an impact on social stability, the business environment, and later policy implementation, and will also hinder local economic development. Therefore, it is important that public officials improve their professionalism. They should be equipped with professional instruments and technical facilities to improve the collection and analysis of pandemic governance monitoring, to enable them to make rapid responses and decisions to some problems in pandemic governance, and to pre-design, accurately predict, and "advance" governance. It is also necessary to appropriately control the administrative accountability of officials, gradually increase public reputation evaluation, carefully evaluate whether the policy objectives and the public medical and health system costs match, and reasonably divide the boundary between social supervision and government supervision to prevent policy overflow and policy overrun.

Internalize the externalities of pandemic governance and reduce the cost of public participation. Public behavior is a core element that affects the consumption of the public medical and health system costs. When medical system resources for pandemic governance are depleted, the public will give up consideration of economic interests, health, and other factors, and choose a behavioral strategy of negative participation and collective protest, so that the governance system becomes unstable. This is not only a warning to remind some public officials who follow the risky behavior of concealing information asymmetry, but will also give the heads of government reassurance. When it comes to pandemic governance issues, officials should "let go" so that the governance of pandemic issues can be more effectively implemented. At the same time, further promoting government efforts to strengthen its active governance strategy may have a negative impact on local economic development (reduce the rent and lower taxation), but it is possible to seek appropriate feedback paths for this, such as transfer payment funds could be used to reduce their overall tax burden, build a complete pandemic monitoring system and monitoring information system, or provide corporate subsidies for technical innovation improvement total factor productivity-economic growth-drives local governments to increase investment in pandemic governance and is a benign interactive cycle chain. In addition, the rational perception of the public toward pandemic governance should be improved through various channels and platforms, such as official media and social organizations, and the public‘s psychological intervention mechanism should be improved. It is also possible to carry out cross-departmental and cross-organization collaborative governance, determine the subsidy intensity based on the public perception of pandemic governance, efficiently handle public letters, visits, complaints and other communication, rationally design participation forms, broaden public participation channels, and reduce public participation costs. This will help to correct public bias and beliefs, promote value recognition, improve public psychological morale.

Limitation and Future Direction

The increasing demands to construct an indicator system and the associated scientific and rigorous selection of indicators mean that it is necessary to consider both micro and macro effects when constructing the indicator system, and to pay attention to both current and long-term interests, i.e., to be comprehensive and focused. Therefore, this study adopted a scientific, statistical method that combined qualitative and quantitative analyses to construct an indicator system for the public medical and health system costs that passed the relevant tests. It also underwent improvements, resulting in a more reasonable structure for the indicator system, a more appropriate number of indicators, and good reliability and validity. This method is a stable and effective measurement framework, which lays a foundation for future research and fills part of the research gap in the public medical and health system costs. It is hoped that this study will help local governments identify the main factors affecting the changes in the public medical and health system costs so that they can propose governance solutions and strategies from a multidimensional perspective, and build a common and integrated public policy support system by 2050 for the emergency management organization system to help with the prevention and control of major pandemics, with joint guarantees for restoration and a stronger post-pandemic collaborative governance network, so as to restore infrastructure, social property, social order, public morale, and government credibility to normal as soon as possible, and precisely control the public medical and health system costs, and better improve the quality and efficiency of pandemic governance. The study of the public medical and health system costs is inevitably a long-term and complex systematic subject. Since there are relatively few related studies in China, and the theory and research system are not perfect, this study had some shortcomings. For example, the concept and index system for the public medical and health system costs may need to be further expanded, and the measurement method should be improved and upgraded, both of which will be addressed in future studies. At the same time, this study will serve as a beginning and contribute to the study of the public medical and health system costs.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Biomedical Ethics Committee of Nankai University No. NKUIRB2022092. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

XL was responsible for reviewing and editing, conceptualization, visualization, software, and methodology. ZZ was responsible for validation and investigation. LL was responsible for supervision. TC was responsible for validation. GL was responsible for visualization. All authors contributed equally to this work, read, and approved the final manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpubh.2022.942043/full#supplementary-material

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Global Trade Pattern of Medical Devices and China's Trade Position: Based on Data From 2001 to 2020

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To depict the evolution of the global trade of medical devices, this study analyzes the spatiotemporal evolution characteristics of global and China's trade patterns of medical devices from 2001 to 2020 based on data from the World Bank and United Nations Commodity Trade Statistics Database, and thereby investigates the status quo of global and China's medical device trade, as well as changes in China's position in the global medical device trade. The findings are as follows. First, the total global trade volume of medical devices is generally on the rise, showing closer network connections. Despite some changes in trade position, the core countries in the global medical device trade network are relatively fixed. The intermediate position of core trading countries has been weakened on the whole, whereas exporting countries have generally assumed an enhanced central position. Communities with geographical proximity have been formed in the global medical device trade network, including two large communities, the Asian-European countries and the Pacific Rim countries, and one small community, the South American countries. Second, with its rapidly growing trade volume of medical devices with other countries, China has now become the fourth largest medical device trading country in the world. Its number of import and export partners has remained relatively stable and continued to increase. Its export markets are relatively concentrated, and a tripartite pattern of import sources has been formed. China has established extensive interdependent relations and almost no one-way dependent relations in the medical device trade. Among its major trading partners for medical devices, the interdependence of China with developed countries/regions, such as European and American countries and Japan, has generally deepened.

Keywords: medical device trade, complex network, topological structure, spatiotemporal pattern, interdependence

INTRODUCTION

Since the reform and opening up of China, Chinese people's awareness of life and health has increased with the improvement of living standards, and the state has paid more and more attention to the healthcare industry. As an important part of the healthcare system reform, the medical device industry is facing important challenges. Medical devices are an important component of human health protection, and the most important basic element in the construction of the medical service system. It is also a knowledge-intensive, highly specialized, and interdisciplinary high-tech industry. In recent years, with the continuous introduction of new medical reform policies in China, the healthcare system reform has attracted widespread attention.

In 2020, the COVID-19 pandemic had a severe impact on international trade and the world economy, posing serious challenges to the global public health system. As the basic equipment for modern healthcare, medical devices have played an important role in the global fight against the pandemic. Moreover, they are also products related to livelihood and health. As the foundation of the modern healthcare system, the development of medical devices is related to the future development of the national health industry. During the COVID-19 pandemic, medical devices, as one of the most important sectors of the healthcare industry, are an important measure of a country's scientific and technological progress, which further highlights its importance to a country's healthcare system. It is foreseeable that countries around the world will pay more and more attention to the medical device industry. In the long run, the outbreak of this pandemic is beneficial to the development of the medical device industry.

THEORETICAL BASIS

The international trade network is a complex economic system composed of interconnected national or regional economies. It is a new hot topic in the field of international trade. It has been studied from different disciplines and perspectives. Most studies investigated the topological structure and characteristics of the trade network based on centrality, community, clustering coefficient, and other measures of the whole industry or a certain sector or product around the world or in a certain region in a specific year or a long period of time through complex network analysis using a binary or weighted network (1–9).

Research on medical devices mainly takes a micro perspective and examines the technological innovation and enterprise efficiency of medical device companies using tools such as case analysis, data envelopment analysis (DEA), and questionnaire survey (10–13). Some studies have also been conducted from the perspective of the industry by investigating the current regulation status, innovation, regulation mechanisms, technical standards, and industry development of medical devices (14–20). However, few studies have been conducted from the perspective of trade.

It is evident from literature review that trade network has become the forefront of theoretical research of social network. Previous studies investigated the characteristics and patterns of trade networks by constructing a binary matrix or weighted directed network, which provides valuable insights for this study. However, further research is still required in this field. First, few studies have looked at the pattern of medical device trade network from the perspective of overall network and research findings on changes in China's position are inadequate. Second, data mining that covers the entire time scale and reflects the evolution process of global medical device trade network needs to be further expanded. The marginal contributions of this study are as follows. This study breaks the linear logic and considers both time and space dimensions. It attempts to characterize the evolution of the global medical device trade network by constructing a 20-year evolution diagram of this network and analyze the pattern of changes in China's position in medical device trade in an objective and comprehensive manner based on global medical device trade data from 2001 to 2020. It is hoped that the results of this study will provide a theoretical basis and decision-making support for China's efforts to cope with the changes in medical device trade pattern and build a medical device trade network system.

METHODOLOGY AND DATA

Methodology

First, Descriptive Analysis of Trade

The world and China's medical device trade trends are analyzed based on changes in total trade volume.

Second, Social Network Analysis

Social Network analysis is employed to examine changes in the measures of the global trade network of medical devices, including network density, average shortest path length, clustering coefficient, centrality, in-degree and out-degree, closeness centrality, betweenness centrality, and trade network group, thereby revealing the evolution characteristics of this network.

Third, Interdependence Index Analysis

To describe the interdependence of China with other countries in the global medical device trade, this study proposes an interdependence equation for medical device trade by drawing on the Grubel-Lloyd index that estimates the intensity of intra-industry trade:

$$DrGL_{i,j} = \left[1 - \left(\frac{\left|DE_{i\to j} - DI_{i\to j}\right|}{DE_{i\to j} + DI_{i\to j}}\right)\right] \tag{1}$$

where $DE_{i\to j}$ is the export of medical devices from country i to country j; $DI_{i\to j}$ is the import of medical devices of country i from country j; and $DrGL_{i,j}$ is the interdependence index between country i and country j in medical device trade, with a value range of [0–1]. If country i only exports/imports medical devices to/from country j, there is only a one-way dependence index between the two countries, and $DrGL_{i,j}$ is 0. If country i's exports to country j are equal to its imports from country j, then the two countries have the greatest trade overlap, and $DrGL_{i,j}$ is 1. The larger the $DrGL_{i,j}$, the higher the interdependence index between the two countries in medical device trade. $DrGL_{i,j} \geq 0.5$ indicates high interdependence between the two countries in medical device trade, $0.2 < DrGL_{i,j} < 0.5$ indicates moderate interdependence, and $DrGL_{i,j} \leq 0.2$ indicates low interdependence.

Data

Based on existing research (21, 22), this study analyzes the global trade of medical devices in detail through empirical study of

TABLE 1 | Measures of global medical device trade network.

Category	Measure	2001	2003	2005	2008	2010	2013	2015	2018	2020
Node centrality	Average node degree	36.28	39.40	40.72	45.78	45.25	47.53	46.25	47.55	46.95
	Out-degree centralization	67.20%	64.00%	62.54%	58.66%	59.37%	56.82%	57.72%	56.08%	56.42%
	In-degree centralization	35.16%	37.08%	36.90%	35.59%	37.57%	40.15%	42.33%	36.85%	37.19%
Network connectivity	Network density	0.3769	0.4093	0.4274	0.472	0.4707	0.4924	0.4858	0.5084	0.5158
	Weighted clustering coefficient	0.499	0.519	0.533	0.560	0.557	0.574	0.569	0.584	0.586
	Average characteristic path length	1.539	1.519	1.501	1.471	1.465	1.453	1.455	1.431	1.419

import and export data of common categories of medical devices defined under Chinese Harmonized System (HS) codes 9018, 9019, 9020, 9021, 9022, and 9402.

With countries/regions involved in the trade of medical devices abstracted as nodes, 80 countries/regions, such as mainland China, the United States, Germany, and South Korea, are selected as the research objects. Given that the imports and exports of medical devices of these countries/regions in 2001–2020 accounted for 99.05% of the world's total, relevant data are highly representative. An 80*80 matrix was created for the trade network of medical devices based on the bilateral trade flows of the 80 countries/regions. The characteristics of this network were analyzed with UCINET software and visualization was performed using Gephi.

RESULT ANALYSIS

Structural Characteristics and Evolution of Global Medical Device Trade

From 2001 to 2020, the global trade volume of medical devices increased rapidly from US$112.963 billion to US$488.256 billion, representing an average annual growth of 7.23%. Changes in total trade volume are the combined result of changes in participating economies and trade volumes. With the continuous expansion of the global trade of medical devices, the number of participants in the trade has been increasing, and the structure of the trade network has become increasingly complex. From 2001 to 2020, the number of participants in the global medical device trade increased from 190 to 230, and the number of trade connections increased from 5,434 to 5,640, representing an increase of 17.39.0% and 6.65%, respectively. The global medical device trade network shows increasing complexity and has spread to all corners of the world.

Numerous Countries Participating in the Global Medical Device Trade and Forming a Closely Connected Network

As observed from the temporal evolution of node centrality and network connectivity (**Table 1**), the global medical device trade network is characterized by asymmetric structures of out-degree and in-degree of nodes and overall increasingly close connection. However, it also has the characteristics of a small-world network: a high clustering coefficient and a small average characteristic path length. Details are given as follows.

First, the number of countries participating in the global medical device trade has increased, but importer and exporter countries have obviously asymmetric structures. From 2001 to 2020, the average number of trading partners of each country increased from 36 to 47, reflecting the trend of increasing trading partners of participating countries. However, the out-degree and in-degree centralization of the medical device trade network are asymmetric, but the gap narrowed slightly. Out-degree centralization decreased from 0.67 to 0.56, while in-degree centralization scores were mostly <0.4.

Second, countries are relatively closely connected in the global medical device trade, representing an integrated trade pattern. In terms of network connectivity, network density in 2020 is 0.5158, which is significantly higher than the 0.3769 in 2001. This means that the trading partners of each country are relatively concentrated, and countries have become more closely connected in medical device trade and formed a dense network, representing an integrated pattern of global medical device trade.

Third, the local clustering of the global medical device trade network has been increasing, and the trade efficiency has improved. From 2001 to 2020, the average clustering coefficient of the global medical device trade network showed an overall increasing trend and remained above 0.5, indicating that more and more trading countries have overlapping "circles of friends." Meanwhile, the average characteristic path length gradually decreased and approached 1.4. This means that only one intermediate country is needed to achieve network connectivity between the trading countries, reflecting the high efficiency of trade realization in the global medical device trade network.

Relatively Fixed Core Countries in the Global Medical Device Trade Network, With a Shift From Intermediate to Central Position

Relatively Fixed Core Trading Countries, With Some Changes in Trade Position

Table 2 shows the ranking of trading countries/regions based on the imports and exports of medical devices in some years. It can be seen that the core exporters and importers in the global medical device trade network are relatively fixed, but there are some changes in trade position. In terms of out-strength, the core exporters were the United States, Germany, France, Switzerland, Ireland and China. Among them, the trade positions of France and Japan declined, that of China improved, and those of the United States and Germany were relatively stable. In terms of in-strength, the United States, Germany, Japan, the

TABLE 2 | Changes in the top ten ranking of economies based on node strength in the global medical device trade network.

Rank	2001		2005		2010		2015		2020	
	Out-strength	**In-strength**	**Out-strength**	**In-strength**	**Out-strength**	**In-strength**	**Out-strength**	**In-strength**	**Out-strength**	**In-strength**
1	United States of America	United States of America	United States of America	United States of America	United States of America	United States of America	United States of America	United States of America	United States of America	United States of America
2	Germany	Germany	Germany	Netherlands	Germany	Germany	Germany	Germany	Germany	Germany
3	Japan	Japan	Netherlands	Germany	Netherlands	Netherlands	Netherlands	Netherlands	Netherlands	Netherlands
4	Netherlands	Netherlands	Ireland	Japan	France	Japan	China	China	China	China
5	France	France	France	France	Switzerland	France	Belgium	Japan	Ireland	Japan
6	Ireland	United Kingdom	Switzerland	United Kingdom	Ireland	China	Ireland	Belgium	Mexico	France
7	United Kingdom	Italy	United Kingdom	Italy	Belgium	Belgium	Switzerland	France	Switzerland	Belgium
8	Switzerland	Canada	Japan	Belgium	China	United Kingdom	Mexico	United Kingdom	Belgium	United Kingdom
9	Mexico	Belgium	Mexico	Canada	Japan	Italy	France	Italy	Singapore	Italy
10	Belgium	China	Belgium	China	Mexico	Canada	Japan	Canada	France	Canada

Netherlands, France, and China were the largest importers of medical devices in the world. Among them, the trade positions of the United States, Germany, and the Netherlands were relatively stable, while that of China remarkably improved.

A Weakened Intermediate Position of Core Trading Countries and an Enhanced Central Position of Exporting Countries

As shown by the spatiotemporal variations in node betweenness centrality and closeness centrality (**Table 3**), the betweenness centrality of the core trading countries of medical devices decreased, but the closeness centrality of exporting countries increased significantly. This means that despite the weakening of exporters' control over the trade network, core exporters still maintained a strong influence due to their enhanced central position. Furthermore, horizontal comparison shows that the betweenness centrality of each country was generally low and most of the top 10 countries were core exporters, including the United States, European countries, such as France and Germany, and Asian countries, such as China and South Korea. Among them, the United States has long been ranked first in terms of betweenness centrality, reflecting that it plays a significant bridging role in the global medical device trade and has absolute control over the global trade network. It should be noted that under the integrated pattern of the global medical device trade network, the United States' trade control decreased from 8.469 in 2001 to 6.381 in 2020. On the other hand, contrary to the decrease of betweenness centrality, most of the core exporters showed an increased closeness centrality. Among them, China's export influence increased significantly, with its ranking improving from outside the top ten to the fourth in terms of closeness centrality. On the whole, the weakened intermediate position of exporters reduced their trade control, whereas their enhanced central position intensified competition among them. This may offer opportunities for medical device importers, such as China, to enhance their control over the global medical device trade.

Formation of Communities With Geographical Proximity in the Global Medical Device Trade Network

The network structure and core node characteristics of the global medical device trade show the pattern of a polycentric seller's market. To further clarify the community distribution characteristics in the trade of medical devices, this study identified the communities in the directed network of global medical device trade in 2020 as an example. Using the Louvain community detection algorithm, three communities reflecting significant geographical proximity were identified: the Asian-European countries (community 1), the Pacific Rim countries (community 2), and the South American countries (community 3; **Figure 1**).

Community 1 is dominated by Asian and European countries. It is the community with the largest trade volume and the largest number of trade relations. It is also a main export area of medical devices. In particular, the exports of Germany and the Netherlands both exceeded US$ 4 billion. The medical device exports of its member countries accounted for 46.53% of the world's total. The trade relations established with them accounted

TABLE 3 | Changes in the top 10 ranking of economies based on centrality in the global medical device trade network.

Measure	Year	1	2	3	4	5	6	7	8	9	10
Betweenness centrality	2001	United States of America	Germany	Italy	France	Netherlands	Japan	Belgium	United Kingdom	Spain	Russian Federation
		8.469	7.08	4.622	4.017	3.837	3.034	2.724	2.711	1.675	1.588
	2005	United States of America	Germany	France	Italy	Netherlands	Belgium	Switzerland	United Kingdom	Russian Federation	Brazil
		9.8	6.062	4.141	3.042	3.012	2.877	2.677	1.843	1.765	1.623
	2010	United States of America	Germany	France	Italy	Switzerland	United Kingdom	Netherlands	Belgium	Egypt	China
		10.721	6.929	3.865	3.341	2.872	2.747	2.637	2.196	1.416	1.341
	2015	United States of America	Germany	France	Netherlands	Switzerland	Belgium	United Kingdom	Italy	Russian Federation	Turkey
		7.911	7.059	4.312	3.148	3.067	2.651	2.55	1.906	1.589	1.388
	2020	Germany	United States of America	Netherlands	China	France	Italy	United Kingdom	Switzerland	Belgium	Brazil
		6.786	6.381	4.659	2.724	2.612	2.525	1.755	1.752	1.603	1.569
In-degree closeness centrality	2001	United Arab Emirates	Iran, Islamic Republic of	Pakistan	Bangladesh	Kuwait	Lebanon	Panama	Ethiopia	Nigeria	Ecuador
		7.411	7.369	7.363	7.342	7.328	7.328	7.308	7.295	7.295	7.268
	2005	Kuwait	Iran, Islamic Republic of	Egypt	Bangladesh	Algeria	Panama	Nigeria	Ethiopia	Qatar	United States of America
		10.408	9.553	9.518	9.416	9.382	9.36	9.36	9.349	9.294	8.977
	2010	United Arab Emirates	Kazakhstan	Kuwait	Algeria	Germany	United States of America	France	United Kingdom	Italy	Netherlands
		22.191	21.644	21.237	21.237	19.363	19.315	18.854	18.72	18.72	18.676
	2015	Ecuador	Algeria	Venezuela, Bolivarian Republic of	Ethiopia	Germany	United States of America	France	Netherlands	Belgium	Turkey
		21.884	21.644	21.067	20.735	19.603	19.363	19.175	19.036	18.9	18.9
	2020	Algeria	Iran, Islamic Republic of	Bangladesh	Lebanon	Ethiopia	Venezuela, Bolivarian Republic of	Germany	United States of America	Netherlands	France
		15.076	15.076	15.019	14.934	14.739	14.549	14.057	13.958	13.86	13.835
Out-degree closeness centrality	2001	Germany	United States of America	France	Netherlands	Italy	United Kingdom	Belgium	Switzerland	Japan	Sweden
		50	50	49.686	49.686	49.375	49.068	48.466	48.466	48.171	47.024
	2005	United States of America	Germany	Netherlands	United Kingdom	France	Italy	Switzerland	China	Belgium	Japan
		98.75	98.75	98.75	98.75	97.531	97.531	97.531	97.531	91.86	91.86
	2010	Germany	United States of America	Netherlands	Belgium	Switzerland	France	United Kingdom	Italy	China	Korea, Republic of
		100	100	100	98.75	98.75	97.531	97.531	97.531	97.531	96.341
	2015	Germany	United States of America	Netherlands	Italy	China	France	Belgium	Korea, Republic of	United Kingdom	Switzerland
		100	100	100	98.75	98.75	97.531	97.531	97.531	96.341	96.341
	2020	Germany	United States of America	Netherlands	China	Italy	United Kingdom	Switzerland	France	Belgium	Korea, Republic of
		100	100	100	100	97.531	97.531	97.531	96.341	96.341	96.341

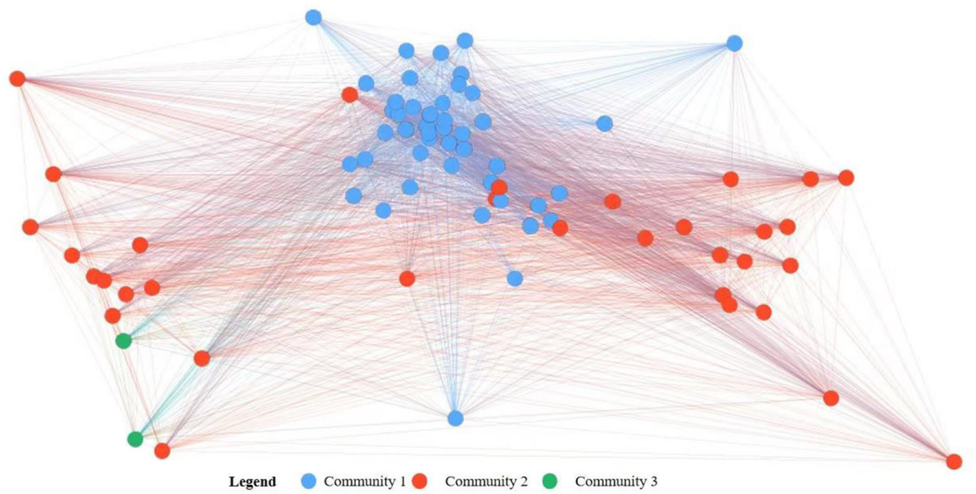

FIGURE 1 | Community detection in the global medical device trade network in 2020.

for 58.12% of the total relations in the global medical device trade network. And the trade relations within the community accounted for 57.61%. In addition, this community includes many major importers of medical devices in the world. Countries with imports of more than US$ 100 million, such as the United Kingdom, Italy, Slovakia, and Romania, accounted for 40% of the total importers within the community. Community 2 is centered around the United States and China, covering 33 countries/regions in Asia, Europe and America. The medical device exports of its member countries accounted for 53.13% of the world's total, and their export relations accounted for 40.43%. The United States and China are the first and second core nodes, respectively, and Japan, a major exporter, is the third core node. Community 3 only includes Chile and Peru and accounted for the smallest proportion of imports (0.26%) and exports (0.61%).

Characteristics of China's Medical Device Trade in the Network

China has been a net exporter of medical devices since 2001. Its trade surplus gradually increased from US$153 million in 2001 to US$25.747 billion in 2020. In particular, its trade surplus in 2020 increased by US$10.2 billion compared with 2018 due to the COVID-19 pandemic. China has now become the fourth largest trader of medical devices in the world. It shows the following characteristics in the import and export network of medical devices.

Increased Imports and Exports

China experienced high growth of medical device imports and exports from 2001 to 2020 according to the node strength and ranking shown in **Table 4**. Its exports increased from US$1.582 billion to 41.880 billion, with its ranking improving from 16th to 4th. Its imports increased from US$1.429 billion to 16.133 billion, with its ranking improving from 16th to 4th. In 2020, due to the COVID-19 pandemic, China demonstrated its strength in the supply and demand of medical devices for the first time, resulting in a substantial increase in exports. China has a high level of participation in the global medical device trade network, with high rankings in terms of both out- and in-strength. However, obvious differences are observed between its import and export trends.

Relatively Concentrated Export Markets and a Tripartite Pattern of Import Sources

Table 5 shows the inter-annual changes in China's major export markets for medical devices and their shares. It can be seen that the share of its top 10 export destinations in its total medical device exports is decreasing year by year. Although the United States, Japan, and Germany remain the main export markets for Chinese medical devices, their market share is decreasing year by year, representing a sharp decrease from 63.91% in 2001 to 34.59% in 2020 of China's total medical device exports.

On the other hand, changes in the in-degree value and ranking of China's medical device trade followed a basically similar trend with those in out-degree. From 2001 to 2020, the number of import sources of China increased from 33 to 51, with the in-degree ranking rising from 15th to 7th. On the whole, China has an increasing dependence on medical device imports and has an increasing number of import sources. Furthermore, based on the inter-annual changes in China's major medical device import markets and their shares in **Table 6**, it can be seen that China's major medical device import sources have gradually changed from North America and Europe to North America, South America, and Europe. In 2001, China had only a few core import sources of medical devices, mainly including North American, European, and East Asian countries/regions, such as Hong Kong (China), the United States, Japan, and Germany. In 2010, China's major import sources of medical devices remained basically unchanged. Meanwhile, the market share of medical

TABLE 4 | China's node degrees, imports and exports, and rankings in the medical device trade.

Category	Measure	2001	2003	2005	2008	2010	2013	2015	2018	2020
Imports and exports	Exports	15.82	25.68	49.91	110.10	134.03	202.87	235.18	318.64	418.80
	Rank by exports	16	14	11	10	8	6	4	4	4
	Imports	14.29	21.72	28.38	45.52	64.20	103.70	114.68	163.14	161.33
	Rank by imports	10	8	10	9	6	5	4	4	4
Node degree	Out-degree	64	71	77	78	77	78	78	78	79
	Rank by out-degree	12	9	7	4	7	5	4	4	2
	In-degree	33	34	35	41	40	42	45	50	51
	Rank by in-degree	15	22	22	14	16	16	11	7	7

TABLE 5 | Changes in China's major export markets for medical devices and their shares.

Rank	2001	Share	2005	Share	2010	Share	2015	Share	2020	Share
1	United States of America	30.12%	United States of America	22.49%	United States of America	23.74%	United States of America	24.26%	United States of America	22.65%
2	Japan	28.90%	Japan	18.32%	Japan	11.65%	Japan	8.83%	Germany	6.34%
3	Germany	4.89%	Germany	6.25%	Germany	6.83%	Hong Kong, China	6.40%	Hong Kong, China	5.91%
4	Hong Kong, China	4.46%	Singapore	4.61%	Hong Kong, China	4.44%	Germany	6.11%	Japan	5.59%
5	United Kingdom	4.18%	Hong Kong, China	4.18%	Netherlands	3.39%	South Korea	3.11%	United Kingdom	3.82%
6	Netherlands	3.14%	Netherlands	3.22%	United Kingdom	2.86%	Netherlands	3.00%	South Korea	3.78%
7	Singapore	3.11%	South Korea	2.51%	India	2.28%	United Kingdom	2.96%	Hungary	2.91%
8	France	1.57%	United Kingdom	1.95%	Russia	2.25%	India	2.82%	Netherlands	2.87%
9	Italy	1.44%	Russia	1.92%	France	2.23%	Singapore	2.53%	Russia	2.56%
10	India	1.28%	Ireland	1.64%	Singapore	2.18%	Australia	1.95%	Brazil	2.42%
Total		83.09%		67.08%		61.85%		61.98%		58.86%

devices imported from European countries, such as Germany, the United Kingdom, the Netherlands, and Switzerland, increased. These countries gradually became important import sources of medical devices for China. In 2020, Asian countries, such as Singapore (3.40%) and South Korea (2.70%), have become important import sources of medical devices for China.

In general, China's medical device import sources have developed into a tripartite pattern consisting of North America, Europe, and Asia. Within this pattern, the main import sources include community 1 and 3 members, such as the United States, Germany, Japan, the Netherlands, Hong Kong (China), and Singapore, together maintaining a share of around 80% in China's medical device market.

Interdependence of China in Medical Device Trade

To characterize the interdependence between China and its trading partners for medical devices, and considering the high concentration of China's medical device trade volume, this study uses the independence index model to calculate China's interdependence index with its major trading partners of medical devices in 2001, 2010, and 2020, respectively (**Table 7**).

In terms of medical device trade, the interdependence between China and developed countries/regions, such as the United States, Hong Kong (China) and Germany, has generally increased, while that with Japan and the United Kingdom has decreased significantly. Furthermore, for most countries/regions with high interdependence with China, China's exports to them were higher than their exports to China in 2020, which indicates that these countries/regions were more dependent on China. However, China was more dependent on these countries/regions in 2001 and 2010. Meanwhile, China's exports to countries/regions with low interdependence have gradually increased and were much higher than their exports to China, resulting in low interdependence but high one-way dependence.

According to the ranking of China's major trading partners by interdependence index (**Table 8**), the number of countries/regions that maintain high interdependence with China on the medical device trade has gradually increased and most of them are developed countries/regions, such as European and American countries and Japan. The number of countries/regions that maintain low interdependence with China has gradually decreased, and there have been no countries/regions that are completely one-way dependent on China.

On the whole, China has established extensive interdependent relations and almost no one-way dependent relations in the medical device trade. Among its major trading partners for

TABLE 6 | Changes in China's major import markets for medical devices and their shares.

Rank	2001	Share	2005	Share	2010	Share	2015	Share	2020	Share
1	Hong Kong, China	26.05%	United States of America	22.65%	United States of America	25.92%	United States of America	28.62%	United States of America	28.36%
2	United States of America	25.73%	Hong Kong, China	17.22%	Germany	16.85%	Germany	15.58%	Germany	17.50%
3	Japan	18.44%	Germany	16.13%	Hong Kong, China	14.96%	Japan	8.71%	Japan	9.35%
4	Germany	10.95%	Japan	15.49%	Japan	12.68%	Singapore	8.56%	Netherlands	7.49%
5	France	2.57%	Singapore	6.48%	Netherlands	3.68%	Hong Kong, China	6.20%	Hong Kong, China	4.98%
6	Singapore	2.02%	Netherlands	3.53%	Singapore	3.02%	Netherlands	5.14%	Singapore	3.40%
7	Netherlands	1.92%	South Korea	2.56%	Switzerland	2.71%	Switzerland	3.69%	Switzerland	3.40%
8	South Korea	1.65%	United Kingdom	2.37%	United Kingdom	2.43%	Belgium	2.77%	Belgium	2.90%
9	United Kingdom	1.60%	France	2.07%	France	1.95%	South Korea	2.58%	South Korea	2.70%
10	Italy	1.17%	Switzerland	1.83%	Israel	1.80%	Israel	2.33%	Israel	2.40%
Total		92.10%		90.32%		86.00%		84.19%		82.48%

TABLE 7 | Interdependence between China and its top 20 trading partners for medical devices in 2001, 2010, and 2020.

Rank	2001		2010		2020	
	Country/region	$DrGL_{i,j}$	Country/region	$DrGL_{i,j}$	Country/region	$DrGL_{i,j}$
1	United States of America	0.7861	United States of America	0.9772	United States of America	0.9818
2	Japan	0.9287	Japan	0.9791	Germany	0.6400
3	Hong Kong, China	0.1731	Germany	0.5947	Japan	0.8744
4	Germany	0.3963	Hong Kong, China	0.4724	Hong Kong, China	0.7867
5	United Kingdom	0.8190	Netherlands	0.9798	Netherlands	0.6638
6	Singapore	0.9205	United Kingdom	0.8979	South Korea	0.7103
7	Netherlands	0.9495	Singapore	0.8583	United Kingdom	0.5051
8	France	0.5048	France	0.9112	Singapore	0.7814
9	South Korea	0.4473	South Korea	0.8738	Belgium	0.7159
10	Italy	0.8127	Switzerland	0.4307	France	0.8622
11	India	0.8924	Italy	0.6184	Hungary	0.0272
12	Ireland	0.9550	India	0.4027	Switzerland	0.2032
13	Spain	0.4542	Belgium	0.9812	India	0.3857
14	Denmark	0.3822	Australia	0.5224	Israel	0.7090
15	Switzerland	0.0345	Russia	0.0295	Russia	0.0225
16	Sweden	0.1598	Denmark	0.8251	Brazil	0.0338
17	Israel	0.3352	Israel	0.3940	Italy	0.5331
18	Taiwan, China	0.3349	Sweden	0.5369	Australia	0.3163
19	Australia	0.6927	Taiwan, China	0.8578	Vietnam	0.7389
20	Canada	0.8389	Brazil	0.0344	Mexico	0.5906

medical devices, the interdependence of China with developed countries/regions, such as European and American countries and Japan, has generally deepened.

CONCLUSIONS AND DISCUSSIONS

Conclusions

This study analyzes the spatiotemporal evolution characteristics of global and China's trade patterns of medical devices from 2001 to 2020 based on data from the World Bank and United Nations Commodity Trade Statistics Database, and thereby investigates the status quo of global and China's medical device trade, as well as changes in China's position in the global medical device trade. The findings are as follows.

First, the total global trade volume of medical devices is generally on the rise. The changes in total trade volume are the combined result of changes in participating economies and trade volumes. The development trends of the number of participating

TABLE 8 | Ranking of China's top 20 trading partners for medical devices by interdependence in 2001, 2010, and 2020.

Interdependence	2001	2010	2020
High	France, Australia, United States of America, Italy, United Kingdom, Canada, India, Singapore, Japan, Netherlands, Ireland	Australia, Sweden, Germany, Italy, Denmark, Taiwan, Singapore, South Korea, United Kingdom, France, United States, Japan, Netherlands, Belgium	United Kingdom, Italy, Mexico, Germany, Netherlands, Israel, Korea, Belgium, Vietnam, Singapore, Hong Kong, France, Japan, United States of America
Medium	Hong Kong (China), Taiwan (China), Israel, Denmark, Germany, South Korea, Spain	Israel, India, Switzerland, Hong Kong (China)	Switzerland, Australia, India
Low	Switzerland, Sweden, Hong Kong (China)	Russia, Brazil	Russia, Hungary, Brazil

economies and trade connections generally correspond to the total trade volume. Connections between countries/regions in the medical device trade have strengthened, which is reflected by increasing interactions and interdependence, and closer network connections. Despite some changes in trade position, the core countries in the network are relatively fixed. The intermediate position of core trading countries has been weakened on the whole, whereas exporting countries have generally assumed an enhanced central position. Communities with geographical proximity have been formed in the global medical device trade network, including two large communities, the Asian-European countries and the Pacific Rim countries, and one small community, the South American countries.

Second, China's trade volume of medical devices with other countries has grown rapidly, exhibiting a continuous upward trend. With its greatly increased imports and exports, it has now become the fourth largest medical device trading country in the world. Its number of import and export partners has remained relatively stable and continued to increase. Besides, its export markets are relatively concentrated, and a tripartite pattern of import sources has been formed. According to the interdependence index, the interdependence between China and developed countries/regions, such as the United States, Hong Kong (China) and Germany, has generally increased in the medical device trade, while that with Japan and the United Kingdom has decreased significantly. China has established extensive interdependent relations and almost no one-way dependent relations in the medical device trade. Among its major trading partners for medical devices, the interdependence of China with developed countries/regions, such as European and American countries and Japan, has generally deepened.

Discussions

Due to the COVID-19 pandemic, the global demand for medical devices has surged. In the context of the persistent pandemic, the international dependence on Chinese medical devices may further increase. Therefore, the following suggestions are made.

First, the application of big data promotes the rapid development of the medical device industry. As the first entry point for collecting patient health data, medical devices have an important strategic position. In addition to providing support for services, deep mining of health big data can also lead the strategic planning and guide the direction of future research and development. Big data mining makes it possible to reduce the workload of doctors during the pandemic, improve the efficiency of diagnosis, and improve the accuracy of diagnostic tests. Big data enables the quality upgrade and structural optimization of the medical device industry, and promotes the high-end leap of the whole industry chain. It can also optimize the allocation of resource elements in the medical device industry and improve total factor productivity. Moreover, digitalization can give birth to new models, new demands, and new forms of the medical device industry, creating new momentum for industrial growth.

Second, since the outbreak of the COVID-19 pandemic, China has demonstrated its strength in supplying medical devices and occupied the global market with numerous medical device orders. China should seize the current opportunities, dedicate more efforts to innovation and research and development, and strengthen international cooperation, especially in the field of high-end medical devices. Meanwhile, efforts should also be made to enhance the international influence of Made in China brands, improve quality standards, continuously strengthen the publicity of Chinese medical device brands, and promote overseas marketing of more pharmaceutical brands.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Spatiotemporal evolution of online attention to vaccines since 2011: An empirical study in China

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Since the outbreak of Coronavirus Disease 2019 (COVID-19), the Chinese government has taken a number of measures to effectively control the pandemic. By the end of 2021, China achieved a full vaccination rate higher than 85%. The Chinese Plan provides an important model for the global fight against COVID-19. Internet search reflects the public's attention toward and potential demand for a particular thing. Research on the spatiotemporal characteristics of online attention to vaccines can determine the spatiotemporal distribution of vaccine demand in China and provides a basis for global public health policy making. This study analyzes the spatiotemporal characteristics of online attention to vaccines and their influencing factors in 31 provinces/municipalities in mainland China with Baidu Index as the data source by using geographic concentration index, coefficient of variation, GeoDetector, and other methods. The following findings are presented. First, online attention to vaccines showed an overall upward trend in China since 2011, especially after 2016. Significant seasonal differences and an unbalanced monthly distribution were observed. Second, there was an obvious geographical imbalance in online attention to vaccines among the provinces/municipalities, generally exhibiting a spatial pattern of "high in the east and low in the west." Low aggregation and obvious spatial dispersion among the provinces/municipalities were also observed. The geographic distribution of hot and cold spots of online attention to vaccines has clear boundaries. The hot spots are mainly distributed in the central-eastern provinces and the cold spots are in the western provinces.

Third, the spatiotemporal differences in online attention to vaccines are the combined result of socioeconomic level, socio-demographic characteristics, and disease control level.

KEYWORDS

vaccine, public health, online attention, spatiotemporal characteristics, GeoDetector

Introduction

In the long history of human beings, vaccines have been a powerful weapon to fight against infectious diseases. Many infectious diseases have been controlled or eliminated by vaccination. Vaccination is one of the most effective and cost-effective measures to prevent infectious diseases in humans at present. Through widespread vaccination, smallpox was eradicated globally in 1979, as declared by World Health Organization (WHO). The incidences of polio, plague, measles, rabies, pertussis, tetanus, viral hepatitis B, etc. have also been dramatically reduced by vaccination. Since the outbreak of Coronavirus Disease 2019 (COVID-19), the Chinese government has taken a number of measures to effectively control the pandemic (1, 2). By the end of 2021, China achieved a full vaccination rate of higher than 85%. The Chinese Plan provides an important model for the global fight against COVID-19. Dr. Bruce Aylward, team leader of the WHO-China joint mission on COVID-19, stated that China was taking a rigorous and innovative approach to standard public health measures (3). By using a large-scale science-driven flexible mechanism, China has prevented the spread of COVID-19 and changed its course. Dr. Aylward also suggested China was the only country to have the most experience and achievements in the fight against COVID-19, and that other countries should learn from China's rapid response mechanism (4).

With the rapid development of mobile networks, Internet search data are widely used in epidemiological research with the ultimate goal of informing public health and policy (5, 6). Internet search data not only enable Internet users to obtain the required disease prevention information in a short period of time but also assist the government and medical institutions in market forecasting. The general public has formed the habit of searching the Internet for information about the COVID-19 pandemic, prevention methods, drug purchases, and the effect of vaccines (7–9). Accordingly, there has been an increasing public search for and interest in vaccines, from routine ones, such as HPV (10–18), HIV (19–22), and polio (23–28), to those that are promoted during pandemics, such as SARS (29–32), H1N1 (33–40), and COVID-19 (41–52). How to determine public concerns about vaccines is becoming the focus of research in government and medical system decision-making. A literature review revealed that research on online attention to vaccines (OAV) mainly investigated different vaccine types (10–52), correlation with vaccination rates (10, 23), impact on vaccination (44, 53), and vaccination demand prediction and trend analysis (54–57) based on internet search data in terms of different disciplines and perspectives. The concept of the online attention has been widely used in the research of public health events, such as vaccines, but it is mostly based on a single platform and English cultural background.

However, the above studies are mostly based on Google search data, which are primarily relevant to English-speaking countries. Additional research is required to determine whether their conclusions are applicable to other cultures, backgrounds, and search engines. Due to the inaccessibility of Google Search, Baidu is the primary search engine used in China. In 2019, Baidu ranked first in China with a penetration rate of 90.9% (58). Hence, Baidu search data better reflect the public need for vaccines in China than other search engines. Baidu Index shows the changes in the search volume of a particular keyword over time, and directly and objectively reflects the interests and needs of Chinese internet users. Baidu has become one of the most important online platforms for statistical analysis in China (59). As of March 2021, Baidu ranked first in the three major search engine markets (all-platform, PC, and mobile) in China (it had a 70.18% share of the Chinese search engine market in March 2021). Therefore, Baidu Index is reliable. Infodemiology studies based on the Baidu Index platform mainly involve the application in COVID-19 prediction and monitoring (60, 61) but have not investigated OAV. In terms of research content, few studies have analyzed the spatial characteristics of OAV and their causes. Therefore, exploring the spatial characteristics of OAV, the influencing factors, and their effects using Baidu Index data will enable the identification of problems from a new perspective and help to understand and manage public health behaviors in the long term. Internet searches using keywords like vaccines reveal the attention of internet users to vaccines, reflect local awareness and needs for vaccines, and provide a basis for global public health policy making.

Accordingly, this study aims to analyze OAV in 31 provinces/municipalities in China (excluding Hong Kong, Macau, and Taiwan) with Baidu Index as the data source and using measures, such as geographic concentration index and coefficient of variation. Moreover, factors affecting OAV in each province/municipality in 2011, 2017, and 2020 were investigated using indicators, such as GDP per capita and urbanization rate.

Data and methods

Data

Just like Google Trends, Baidu Index follows certain rules for calculation and retrieval (62). Data collected from Baidu Index is standardized. It allows researchers to select data from different geographic regions, across gender and other characteristics, during a defined sampling time frame.

To examine the Chinese people's attention to vaccines, data for this study are from Baidu Index (https://index.baidu.com/). Searches using the keyword "vaccine" on https://www.aizhan.com/ and https://www.chinaz.com/ revealed that search terms with the highest search volumes were "vaccine," "COVID-19 vaccine," "HPV vaccine," "9-valent vaccine," and "vaccination." At the same time, we took into account that Baidu Index included mobile data in its calculation in 2011, therefore, using these terms as the keywords, the internet search index for the vaccine from January 1, 2011 to December 31, 2021 was calculated to reflect the degree of online attention of interested people/potentially interested people and its changes.

However, keyword data are time sensitive. For example, data on "The COVID-19 vaccine" were not available until February 24, 2020. Therefore, the data sampling period for the empirical part of this study is between February 24, 2020 and December 31, 2021. The same approach was adopted for the data sampling period of the remaining vaccine keywords.

The Baidu Index data revealed a significant trend: Chinese people were more concerned about vaccination status in China. Global vaccination status had no significant impact on searches in China. For example, Baidu Index did not increase significantly on September 21, 2020, when the WHO announced the global COVID-19 vaccine program, COVAX. At that time, vaccination had achieved great success in China, which was significantly different from the situation in other countries.

In terms of research data on influencing factors, GDP size, GDP per capita, urbanization rate, age structure, education, year-end permanent population, sex ratio, infectious disease incidence, and infectious disease mortality were selected as the influencing factors. Data on infectious disease incidence, infectious disease mortality, and sex ratio were from the China Health Statistical Yearbook; data on sex ratio were from 2010, 2016, and 2020 census; and data on the remaining influencing factors were from the China Statistical Yearbook.

Methods

The spatiotemporal differences in OAV in China since 2011 were assessed using five measures, including coefficient of variation (CV), Herfindahl index (H), primacy index (P), geographic concentration index (G), and seasonal concentration index (S). Influencing factors were analyzed using GeoDetector.

Coefficient of variation (CV) is the ratio of the standard deviation to the mean and shows the degree of variability among the sample measures.

$$CV = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})}{n}}/\bar{x}$$

where CV is the degree of variability in OAV among regions. The larger the CV, the more significant the spatial variability in OAV.

Herfindahl index (H) is a comprehensive measure of concentration, reflecting the degree of agglomeration of the regional economic scale. Its value ranges from 0 to 1. The closer it is to 0, the lower the degree of regional economic agglomeration.

$$H = \sum_{i=1}^{n} P_i^2$$

where P_i is the ratio of the index of a particular location to the total number. The closer H is to 1, the higher the regional agglomeration of OAV.

Primacy index (P) is a relevant measure in economies of scale and agglomeration and is measured by the ratio of the economic scale of the first-ranked region to that of the second-ranked region, reflecting the degree of agglomeration of regional economies.

$$P = P_1/P_2$$

where P_1 and P_2 are the OAV in the regions with the first and second largest scales, respectively. It aims to analyze the concentration of OAV. The larger the P, the more concentrated and uneven the OAV is.

The geographic concentration index (G) is a measure of the geographical concentration of economic activity. It reflects the regional concentration or dispersion of OAV. The closer the G is to 100, the more concentrated the OAV is in a particular region; otherwise, the more dispersed it is.

$$G = 100\sqrt{\Sigma_{i=1}^{n}\left(P_j/P\right)^2}$$

where P_j is the OAV in region j, and P is the total OAV.

Seasonal concentration index (S) reflects the temporal concentration of OAV.

$$S = \sqrt{\sum_{i=1}^{12}(x_i - 8.33)^2/12}$$

where x_i is the ratio of the monthly to annual total OAV. The larger the S, the more uneven the distribution throughout the year, and the greater the temporal variability in OAV, and vice versa.

Global spatial autocorrelation (Moran's I) is used to test the spatial distribution of OAV among provinces/municipalities in China. It is calculated as follows:

$$I = \frac{\sum_i^n \sum_{j \neq i}^n W_{ij}}{S^2 \sum_i^n \sum_{j \neq i}^n W_{ij}}$$

where $S^2 = \frac{1}{n} \sum_i^n (x_i - \overline{x})^2$, x_i is the attribute value at i, x is the arithmetic mean of x_i, and W_{ij} is the spatial weight matrix.

For hot and cold spot analysis (Getis-Ord G_i), according to Getis and Ord (63), the Gi statistic for each area unit i is:

$$G_i = \frac{\sum_j w_{ij}}{\sum_j x_j}$$

where w_{ij} is the spatial weight value (the spatial weight matrix using the same determination method and specific form as above in Moran's I), and x_j is the observed value of unit j.

GeoDetector is a spatial analysis model used to assess the relationship between a geographical attribute and its explanatory factors (64). It is widely used to investigate the influencing factors of natural and socioeconomic phenomena. GeoDetector requires only a few preconditions and has obvious advantages when dealing with mixed-type data. The factor detector in GeoDetector was used to assess the explanatory power of each influencing factor and its changes in the evolution of OAV. The factor detector is expressed as follows:

$$q = 1 - \frac{\sum_{h=1}^L \sigma_h^2 N_h}{N\sigma^2}$$

where q is the detection capability of an influencing factor for OAV; h = 1... L is the classification of each factor of the variable; L is the number of secondary provinces/municipalities; σ^2 is the variance of OAV in primary provinces/municipalities; σ_h^2 is the variance of OAV in secondary provinces/municipalities; N is the number of primary provinces/municipalities, and N_h is the number of secondary provinces/municipalities. The value range of q is [0, 1]. The larger the q, the greater the influence of this factor on OAV in each province/municipality.

Spatiotemporal evolution of OAV

Temporal evolution of OAV

As shown in Figure 1, the total OAV in China increased dramatically from only 890,000 in 2011 to 38,487,600 in 2021, exhibiting a general upward trend. Since 2013, a series of vaccine scandals, such as illegal vaccines in Shandong, and falsification of rabies vaccine production records, had drawn public attention to vaccines. Such attention began to increase significantly in 2016 when the HPV vaccine for cervical cancer prevention was approved in China. There had been a dramatic increase in OAV since 2019 due to the COVID-19 pandemic. Moreover, OAV in the eastern region increased from 379,700 in 2011 to 18,317,000 in 2021, always higher than the national level and those in the central and western regions. OAV in the central region was slightly higher than that in the western region. It generally exhibited a decreasing trend from the eastern to central to western regions.

The ratios of OAV of each month to the monthly average were calculated in Table 1. Except for a few years, the ratios for March, May, July, August, and December were all >1. In particular, the ratio for July was 1.20, and that for August was 1.15. These 5 months can be considered the peak season for vaccine searches. The ratios for January and February were between 0.7 and 0.9, and these 2 months are thus defined as the off-season for vaccine searches. The ratios for April, June, September, October, and November were between 0.9 and 1, and these 5 months are regarded as the shoulder season for vaccine searches. The seasonal concentration index of OAV was >4 from 2011 to 2021, with an average of 5.73, indicating uneven monthly distribution and obvious seasonal differences in OAV in China. The monthly data were aggregated into quarterly data according to the conventional definition of seasons to analyze the quarterly distribution of OAV. In the 2011–2021 period, the indices of OAV in spring, summer, autumn, and winter were 1966.06, 2706.84, 2664.12, and 2339.34, respectively. Summer and autumn are the seasons with higher OAV. Between 2015 and 2019, the average Herfindahl index of national OAV was <0.1, which once again demonstrates the uneven monthly distribution and significant seasonal differences in OAV. In addition, it is worth noting that the month-on-month growth rates in 2020 are larger than those in 2019 due to the COVID-19 pandemic.

Spatial differences in OAV

As shown in Table 2, there were obvious geographical imbalances in OAV in China. The highest OAV was measured in Guangdong, Jiangsu, Zhejiang, Beijing, Shandong, and Shanghai in the eastern region, and Henan in the central region. In 2011, the top 10 provinces/municipalities in terms of OAV were Beijing, Shandong, Guangdong, Zhejiang, Henan, Shanghai, Jiangsu, Hebei, Hubei, and Shaanxi, accounting for 47.33% of the national total. In 2016, the top 10 provinces/municipalities were Guangdong, Beijing, Zhejiang, Jiangsu, Shanghai, Sichuan, Shandong, Henan, Hubei, and Fujian, accounting for 53.74% of the national total. In 2021, the top 10 provinces/municipalities were Guangdong, Jiangsu, Shandong, Zhejiang, Beijing, Henan, Sichuan, Hebei, Shanghai, and Anhui, accounting for 54.21% of the national total. The proportion of the top 10 provinces/municipalities in 2021 was greater than those in 2011 and 2016, indicating increasing regional differences in OAV in China.

To describe the regional differences in OAV among the 31 provinces/municipalities in mainland China, a comprehensive

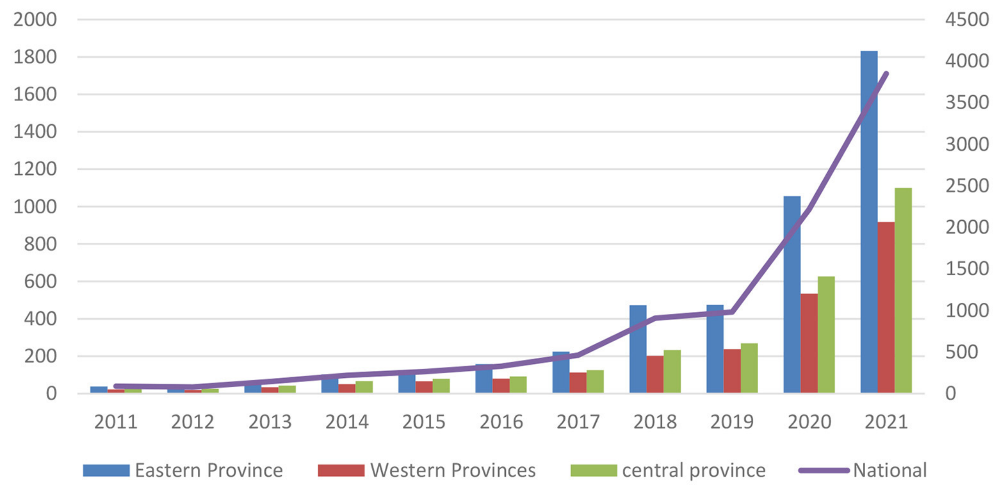

FIGURE 1
Changes in OAV from 2011 to 2019 (unit: 10,000).

TABLE 1 OAV in each month in China between 2011 and 2019 (unit: 10,000).

Month	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
January	6.1276	4.9510	5.9715	16.4322	20.0434	24.9498	25.8065	44.9147	86.4358	105.1819	288.0900
February	6.5009	7.0802	4.9862	15.5325	16.2985	19.6666	29.1536	35.7974	76.8815	91.2497	192.8527
March	8.9300	8.1371	6.4715	18.4995	22.0646	73.2747	36.4584	56.2070	105.0223	145.2502	360.8367
April	8.4635	7.5255	6.9264	17.2114	21.9430	32.5817	34.1198	51.9747	96.6469	220.1395	364.6814
May	8.7205	7.7090	6.4421	18.1131	23.3494	23.2284	36.5213	82.6084	91.4421	210.4564	463.0280
June	6.9701	6.6224	10.2082	18.4731	22.3731	18.0805	37.1406	68.8988	70.5800	184.2741	429.3844
July	7.1055	6.6405	17.8827	18.9855	23.3171	27.6589	41.0535	195.5302	83.7499	186.6123	396.2210
August	7.5100	6.6981	16.0618	20.8088	25.0268	22.4641	61.3631	83.2805	112.8623	208.6294	361.8486
September	7.2869	6.0434	16.9765	19.7048	23.2770	20.3736	43.4552	72.6461	86.0873	194.4381	242.5200
October	7.5118	6.3923	15.8647	20.7279	23.1627	21.4055	40.2597	73.2803	62.5353	192.8964	245.6573
November	7.4786	6.1858	15.5996	19.9718	22.0601	22.2290	41.8450	81.6458	57.2416	197.4531	272.7819
December	7.0885	5.8339	22.2645	18.0137	24.9450	27.7352	43.5862	79.5985	68.6763	313.1543	274.2530
Seasonal concentration index	4.0275	4.2014	10.4125	3.9040	4.0846	6.3835	4.9364	7.7947	4.8419	6.8597	5.5764
Herfindahl index	0.0843	0.0847	0.1015	0.0839	0.0842	0.1052	0.0872	0.1043	0.0865	0.0904	0.0884

analysis was conducted using the coefficient of variation, Herfindahl index, geographic concentration index, and primacy index (Table 3).

Large spatial differences with unstable fluctuations were found in OAV in the 2011–2021 period. The coefficient of variation in the 10-year period was approximately 0.54 on average and increased ear by year. The Herfindahl index was close to 0 and showed small fluctuations, indicating low agglomeration and obvious spatial dispersion of OAV among the various provinces/municipalities. The primacy index remained <2 and fluctuated slowly, and the geographic concentration index was also small, indicating moderate agglomeration and normal spatial structure of OAV among the various provinces/municipalities.

Moreover, there were spatial differences in OAV among the eastern, central, and western regions in the 2011–2021 period. The coefficient of variation maintained a fluctuating growth year by year, with the lowest degree of difference among the three regions in 2011. The Herfindahl index was approximately 0.36 and generally increased year by year, indicating a spatial concentration trend of OAV. The primacy index remained <2 and increased year by year, indicating that there was an increasing difference in OAV between the first and second-ranked regions. The average geographical concentration index was 60.37, and the gap was widening. It suggests that OAV was increasingly concentrated in a particular region from 2011 to 2021.

TABLE 2 OAV in each province/municipality between 2011 and 2021 (unit: 10,000).

Province/municipality	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Total
Anhui	3.02	2.70	4.56	7.47	8.80	10.14	14.36	29.13	35.28	83.81	143.82	350.59
Beijing	4.77	4.61	8.98	13.24	14.86	20.57	27.47	65.34	57.21	132.97	201.91	561.52
Fujian	3.37	3.10	6.02	9.04	10.32	12.52	16.59	29.78	32.68	71.50	125.18	326.82
Gansu	1.93	1.74	2.43	3.69	4.67	5.33	7.80	13.41	15.94	35.76	64.85	161.74
Guangdong	4.67	4.21	9.91	15.45	19.18	28.58	40.15	85.65	83.41	184.65	347.54	838.68
Guangxi	2.71	2.11	3.99	5.70	7.49	7.99	10.66	19.23	22.97	49.95	95.54	233.82
Guizhou	1.59	1.14	2.38	3.38	5.45	6.43	9.33	15.76	19.17	41.19	74.09	184.15
Hainan	1.11	0.81	1.39	2.26	3.64	4.38	6.54	12.77	13.49	25.91	42.70	117.58
Hebei	3.98	3.62	5.90	8.83	10.32	11.80	15.13	31.64	33.47	91.95	163.17	388.90
Henan	4.26	3.81	6.35	9.90	11.49	13.95	17.51	35.19	42.46	102.14	192.82	449.82
Heilongjiang	2.86	2.52	3.75	5.63	7.20	7.70	10.42	18.20	20.50	52.00	85.27	221.64
Hubei	3.55	3.16	5.93	8.87	10.73	13.20	17.87	32.44	37.00	82.96	132.39	355.22
Hunan	3.37	2.81	5.45	8.68	10.10	11.39	17.11	30.23	33.48	71.00	136.32	336.69
Jilin	2.56	2.33	3.42	4.93	6.41	7.50	10.03	17.56	20.29	45.89	76.71	202.29
Jiangsu	4.04	3.65	7.77	12.14	14.34	18.91	31.01	62.87	65.93	136.45	255.40	625.01
Jiangxi	2.50	2.45	3.84	6.37	7.69	8.61	12.81	22.78	26.76	59.12	102.73	261.52
Liaoning	3.46	2.88	4.93	7.86	8.92	10.20	14.28	26.89	29.01	71.05	121.78	308.89
Inner Mongolia	1.82	1.57	2.64	3.91	5.39	5.94	8.36	14.89	17.60	41.70	71.05	179.10
Ningxia	0.64	0.43	0.75	1.08	1.52	2.12	3.90	6.54	8.16	19.07	31.74	77.85
Qinghai	0.37	0.33	0.57	0.76	0.97	1.70	3.22	6.06	7.63	16.60	28.09	67.93
Shandong	4.70	4.12	7.71	11.54	12.69	16.11	19.82	45.10	49.35	127.13	228.85	539.00
Shanxi	3.15	2.85	4.40	6.84	7.61	8.74	11.01	20.47	24.29	58.76	107.86	262.21
Shaanxi	3.55	3.15	5.24	7.91	9.15	10.76	14.22	25.49	31.53	66.95	121.42	304.69
Shanghai	4.13	3.75	7.37	11.05	13.11	17.73	26.88	55.39	48.93	103.70	160.37	461.51
Sichuan	3.21	3.09	6.12	9.05	11.45	16.63	20.85	40.42	45.51	105.97	163.86	434.55
Tianjin	2.72	2.50	4.41	6.73	7.66	8.38	10.77	20.89	22.61	49.68	77.88	218.54
Tibet	0.20	0.15	0.19	0.28	0.34	0.64	1.62	3.63	4.82	11.76	19.47	44.35
Xinjiang	1.88	1.39	2.03	3.24	4.32	5.22	6.94	11.86	14.19	37.71	55.97	148.32
Yunnan	2.20	2.03	3.52	5.65	6.91	7.72	11.33	18.77	21.44	49.97	95.79	230.68
Zhejiang	4.47	4.25	8.41	12.62	14.28	19.02	30.01	63.53	67.41	132.16	228.71	595.63
Chongqing	2.21	2.06	3.84	6.15	8.13	9.89	14.55	25.52	28.39	58.28	95.51	259.66

Furthermore, Table 4 was prepared to measure OAV within the eastern, central, and western regions in mainland China. The comparison revealed obvious spatial differences in OAV within eastern, central, and western China in the 2011–2021 period. The coefficient of variation generally showed a decreasing trend from the western to eastern to central regions. It indicates that the spatial difference in OAV was relatively large in the western region and relatively small in the central region and that internet users in all provinces/municipalities in the eastern region generally paid close attention to vaccines. From 2011 to 2021, the Herfindahl index in all three regions was >0.1 and fluctuated only slightly. It suggests that OAV was dispersed within each region, without excessive aggregation in one or a few provinces/municipalities. Geographic concentration indices in the three regions fluctuated slightly between 32 and 34 in the 2011–2021 period, indicating a low agglomeration and spatial dispersion of OAV in each region. In the 10-year period, the primacy indices of OAV in all three regions were >1 and remained stable. It suggests that there were small differences between the first and second-ranked provinces/municipalities, indicating a low agglomeration and balanced spatial structure of OAV within each region.

Global Moran's I was used to preliminarily examine the spatial agglomeration characteristics of OAV, and very significant results (Moran's I = 0.119711, Z-score = 2.858161, p = 0.004261) were obtained, indicating a strong spatial autocorrelation for OAV. It fully demonstrates the spatial characteristics of high and low-value agglomeration of OAV in China.

The distribution of hot and cold spots of OAV in China was determined by using the G_i statistic to detect local hot spots. The G_i statistic was divided into four levels from high

TABLE 3 Differences in OAV among provinces/municipalities and among the three regions in China from 2011 to 2021.

Year	Differences among provinces/municipalities				Differences among three regions			
	CV	P	G	H	CV	P	G	H
2011	0.4339	1.0156	19.5774	0.0383	0.2165	1.3221	59.0732	0.3490
2012	0.4618	1.0829	19.7854	0.0391	0.2399	1.3576	59.3726	0.3525
2013	0.5283	1.1037	20.3115	0.0413	0.3010	1.5916	60.2934	0.3635
2014	0.5268	1.1666	20.2974	0.0412	0.2973	1.5464	60.2321	0.3628
2015	0.4935	1.2909	20.0271	0.0401	0.2632	1.5248	59.7016	0.3564
2016	0.5688	1.3896	20.6636	0.0427	0.3120	1.7281	60.4794	0.3658
2017	0.5790	1.2948	20.7532	0.0431	0.3236	1.7891	60.6819	0.3682
2018	0.6585	1.3108	21.5041	0.0462	0.4008	2.0309	62.1995	0.3869
2019	0.5803	1.2373	20.7651	0.0431	0.3215	1.7634	60.6450	0.3678
2020	0.5615	1.3533	20.5985	0.0424	0.3073	1.6851	60.3994	0.3648
2021	0.5836	1.3608	20.7952	0.0432	0.3080	1.6656	60.4112	0.3650

to low by Jenks's natural breaks (Figure 2). The results show that hot and cold spots are distributed in east and west China, respectively, and have clear boundaries. The hotspots are mainly distributed in the central-eastern coastal provinces, of which the Yangtze River Delta provinces are the core hot spot area. The remaining central-eastern region is the sub-hot spot area. The average OAV was 3,060,700 in this region. The eastern coastal region is developed in the traditional sense, where China's three major urban agglomerations are located. On the one hand, this region has a large number of permanent residents and a dense population, and on the other hand, it has a high level of education, thus resulting in high demand and awareness of vaccines. The cold spots are distributed in the western region, including Xinjiang, Tibet, and Qinghai. The average OAV was 868,700. Specifically, Tibet and Qinghai are the core cold spot area, and Xinjiang is the sub-cold spot area. The western region, especially the northwest region, is relatively insensitive to vaccines due to its deep inland location and low population density. On the whole, the spatial distribution of OAV can be preliminarily attributed to the socioeconomic conditions and population size based on the differences in the distribution of hot and cold spots between east and west China. In other words, socioeconomic conditions and population size promote OAV to a certain extent.

Influencing factors of OAV

Selection of influencing factors of OAV

Considering comprehensiveness and data availability, and due to the fact that the influencing factor indicators in 2021 have not yet been published, provincial/municipal OAV in 2011, 2017, and 2020 was used as the explained variable. In particular, 2017 was also selected to detect the changes in influencing factors after the approval of the HPV vaccine for cervical cancer prevention. The correlation coefficients between OAV and its influencing factors were calculated using 13 explanatory variables, such as GDP, per capita GDP, urbanization rate, and infectious disease incidence. Before employing the GeoDetector, the independent variables were stratified by natural breaks using ArcGIS. Each influencing factor was divided into five classes. Consistent classification criteria were applied at different stages. Finally, the GeoDetector was used to measure the influence of each influencing factor on OAV. The results are shown in Table 5.

Result analysis of influencing factors of OAV

The GeoDetector results show that only 6–7 of the 13 factors have an influence on the spatial distribution of OAV, indicating that the distribution of OAV is affected by various factors, such as the economic strength and level of disease control of the provinces/municipalities. The explanatory power of each influencing factor is between 40 and 90%. They can be divided into primary and secondary influencing factors according to the explanatory power. The primary influencing factors include infectious disease incidence and GDP size. Secondary influencing factors include the number of people aged 15–64, the number of people aged 65 and above, the number of people in junior college or higher education, and the year-end population.

TABLE 4 Intra-regional differences in OAV from 2011 to 2021.

Year	CV			*P*			G			H		
	East	West	Central	East	West	Central	East	West	Central	East	West	Central
2011	0.2852	0.5420	0.1617	1.0156	1.2861	1.1658	32.8838	32.8356	33.7662	0.1081	0.1078	0.1140
2012	0.3053	0.5893	0.1479	1.0829	1.2991	1.1928	33.0641	33.5074	33.6957	0.1093	0.1123	0.1135
2013	0.3472	0.6249	0.2016	1.1037	1.3924	1.2425	33.4742	34.0406	34.0036	0.1121	0.1159	0.1156
2014	0.3465	0.6264	0.2061	1.1666	1.3264	1.2461	33.4675	34.0637	34.0339	0.1120	0.1160	0.1158
2015	0.3390	0.5927	0.1844	1.2909	1.3057	1.2296	33.3900	33.5574	33.8956	0.1115	0.1126	0.1149
2016	0.4113	0.6327	0.2144	1.3896	1.5891	1.3278	34.1930	34.1609	34.0906	0.1169	0.1167	0.1162
2017	0.4396	0.5535	0.2086	1.2948	1.3880	1.2183	34.5441	32.9947	34.0511	0.1193	0.1089	0.1159
2018	0.4639	0.5837	0.2330	1.3108	1.5838	1.4256	34.8601	33.4260	34.2265	0.1215	0.1117	0.1171
2019	0.4379	0.5547	0.2425	1.2373	1.5686	1.3867	34.5221	33.0119	34.2994	0.1192	0.1090	0.1176
2020	0.4229	0.5484	0.2414	1.3533	1.5489	1.2644	34.3347	32.9234	34.2907	0.1179	0.1084	0.1176
2021	0.4628	0.5196	0.2697	1.3608	1.3495	1.3407	34.8446	32.5325	34.5246	0.1214	0.1058	0.1192

Level of disease control

The incidence of infectious diseases has the most significant influence on the spatial distribution of OAV. q values were at least as high as 0.86, indicating that the incidence of infectious diseases has a great influence on OAV in each province/municipality. Infectious diseases pose a great threat to public health. Vaccination is the most cost-effective and effective public health intervention for the prevention and control of infectious diseases. For families, it is also an effective means to reduce the incidence of diseases and consequent medical expenses. The incidence of infectious diseases (1/100,000) in China decreased from 2139.69 in 1955 to 190.36 in 2020 as a result of vaccination. The mortality (1/100,000) also decreased from 18.43 in 1955 to 1.87 in 2020. The influence of infectious disease incidence on OAV in 2017 (0.8634) decreased compared with 2011 but increased again in 2020, which might be due to the outbreak of COVID-19.

Socioeconomic level

The influence of GDP size on OAV is self-evident. The greater the GDP size, the more developed the urban infrastructure and services, and the higher the level of informatization. The regression results revealed that except for 2017, the q-values were all >0.8. The more developed a region is, the better the public understanding of vaccines, and the better the health services and facilities, leading to higher public attention to vaccines. The influence of GDP size on OAV increased significantly in 2020 as compared to 2011 to 2017, which may be related to the fact that most COVID-19 cases occurred in relatively developed regions. GDP per capita reflects the local per capita income level to a certain extent. This influencing factor was only significant in regression analysis for 2017, which may be related to the approval of the HPV vaccine for cervical cancer prevention. The total HPV vaccination costs ranged from more than one thousand yuan to even tens of thousands of yuan which included extra costs incurred due to its scarcity. This is a high cost and thus people with higher incomes are more likely to consider vaccination. In recent years, many provinces/municipalities have provided free vaccination for females of the appropriate age, thus making this influencing factor insignificant. The influence of the urbanization rate was not significant in regression analysis, and the q-value decreased year by year. This result is closely related to the improvement of rural infrastructure and the popularization of the Internet in the process of rural revitalization in China in recent years. According to the *48th Statistical Report on the Development of Internet in China*, as of June 2021, the Internet penetration rate in China's urban and rural areas was 78.3 and 59.2%, respectively, and the gap in Internet penetration between urban and rural areas is narrowing year by year.

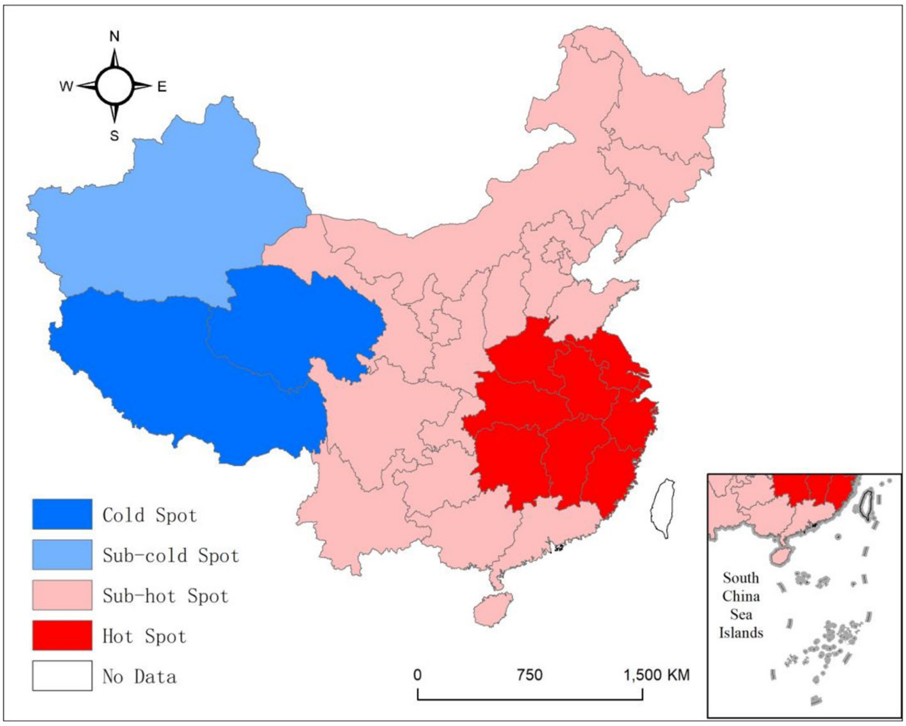

FIGURE 2
Distribution of hot and cold spots of OAV in China.

TABLE 5 Correlation coefficient between OAV and its influencing factors.

Influencing factor			Correlation			Driving effect
			2011	2017	2020	
Socioeconomic level	GDP size		0.8391***	0.7590***	0.8753***	↑
	GDP per capita		0.3738	0.5431**	0.4199	↑
	Urbanization rate		0.3809	0.3661	0.2572	↓
Socio-demographic characteristics	Age structure	0–14 years	0.3524	0.3980	0.4323	↑
		15–64 years	0.6188***	0.5181**	0.6427***	↑
		65 years or older	0.6285***	0.4874**	0.5876***	↓
	Education	Junior college or above	0.7786***	0.4819**	0.6409***	↑
		High school	0.3658	0.2601	0.4093	↑
		Junior high school	0.3134	0.2799	0.4206	↑
	Year-end population		0.6085***	0.5242**	0.6404***	↑
	Sex ratio		0.1258	0.0733	0.0826	↓
Level of disease control	Infectious disease incidence		0.9007***	0.8634***	0.9087***	↑
	Infectious disease mortality		0.0671	0.0456	0.0694	↑

**, ***Significance at the 5, and 1% levels, respectively.
↑The upward arrow represents the correlation between vaccine network attention and a certain influencing factor, which is numerically larger in 2020 than in 2011 or 2017.
↓The downward arrow represents the correlation between vaccine network attention and a certain influencing factor, which is numerically smaller in 2020 than in 2011 or 2017.

Socio-demographic characteristics

In terms of age structure, the influence of children aged 0–14 was not significant. This may be related to China's childhood immunization program, which implements free and mandatory vaccination for children at this age stage. The influences on people aged 15–64 and those aged 65 and above were not significant. One possible reason is that these groups already have some understanding of vaccines. Another possible reason is that according to the *48th Statistical Report on the Development of Internet in China*, more than 80% of Chinese internet users are over the age of 20. Hence, these groups also constitute the main body of internet users. A significant influence was observed for people with the junior college or higher education, indicating that OAV in each province/municipality in China was indeed affected by local education levels. The regression results from GeoDetector for the year-end population were also significant, indicating that the population size of provinces/municipalities also influenced OAV and that this influence increased year by year.

Conclusions and implications

Conclusions

This study investigated the characteristics and spatial evolution of OAV in 31 provinces/municipalities in China since 2011 by spatial data analysis and analyzed the influencing factors by GeoDetector. The following conclusions are drawn:

First, the overall OAV in China showed a rising trend from 2011 to 2021, especially after 2016 due to the HPV vaccines for cervical cancer prevention and the COVID-19 vaccines. The peak season for OAV is May, December, March, August, and July. The monthly distribution of OAV in China was uneven, with obvious seasonal differences.

Second, in the 2011–2021 period, there were significant differences in OAV among provinces/municipalities in China, exhibiting a spatial pattern of "high in the east and low in the west." The highest OAV was measured in Guangdong, Jiangsu, Zhejiang, Beijing, Shandong, and Shanghai in the eastern region, and Henan in the central region. There were large spatial differences with unstable fluctuations, low agglomeration, and obvious dispersion of OAV among provinces/municipalities in the 2011–2021 period. There was an increasing spatial concentration trend of OAV among the eastern, central, and western regions, and an increasing difference between the first and second-ranked regions in the 2011–2021 period.

Third, there were differences in OAV within the eastern, central, and western regions. From the perspective of inter-regional differences, the coefficient of variation generally showed a decreasing trend from the western to eastern to central regions. The Herfindahl index in all three regions was >0.1 and fluctuated only slightly, suggesting that there was no excessive aggregation of OAV in one or a few provinces/municipalities. The primacy indices of OAV in all three regions were >1 and remained stable. The geographic concentration index fluctuated between 32 and 34. It suggests that there were small differences between the first and second-ranked provinces/municipalities, indicating a dispersion, low agglomeration, and balanced spatial structure of OAV within each region.

Fourth, OAV in China showed the spatial characteristics of high and low-value agglomeration. The hotspots are mainly distributed in the central-eastern coastal provinces, of which the Yangtze River Delta provinces are the core hot spot area. The remaining central-eastern region is the sub-hot spot area. The cold spots are distributed in the western region. The spatial distribution of OAV can be preliminarily attributed to the socioeconomic conditions and population size. In other words, socioeconomic conditions and population size promote OAV to a certain extent.

Fifth and lastly, the GeoDetector analysis shows that socioeconomic level, socio-demographic characteristics, and disease control level are the main factors influencing the spatiotemporal differences in OAV. Specifically, the primary influencing factors include infectious disease incidence and GDP size. Secondary influencing factors include the number of people aged 15–64, the number of people aged 65 and above, the number of people in junior college or higher education, and the year-end population.

Implications and suggestions

The results of this study provide some implications for policy-makers.

First, vaccine awareness is generally low in remote areas, such as western China. Local governments need to improve the public's knowledge of infectious diseases and the benefits of vaccination to increase the vaccination rate in appropriate age groups. In particular, given that the COVID-19 pandemic has not ended, much still remains to be done to promote COVID-19 vaccination. Although remote areas are sparsely populated, there is still a great risk of COVID-19 exposure from other areas. Vaccination is the most effective measure to control the COVID-19 pandemic at present. There is an urgent need to raise public awareness on vaccination for the prevention of COVID-19.

Second, some vaccines, such as HPV vaccines, may have high costs. Wherever possible, local governments should try their best to offer convenient medical insurance at a low price, and reduce the cost of vaccination by measures such as medical insurance funds or partner assistance to reduce the incidence of infectious diseases.

Third and last, there are differences between young and middle-aged people and the elderly in the ways and convenience of receiving information. Hence, different measures should be implemented for different age groups for publicity of vaccines and infectious diseases. For example, offline publicity can be given to the elderly through senior activity centers.

Despite its contribution, this study has some limitations. On the one hand, the Baidu engine is not the only search tool used by Chinese internet users. In recent years, with the rise of large online platforms, such as 360 and Sogou, other search engines have also been used. Therefore, the data used for this study are not comprehensive enough. On the other hand, the influencing factors included in this study are still limited. There may be other influencing factors that need to be addressed. Further research is also required to better understand the mechanism of the influencing factors.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

Author contributions

All authors undertook research, writing, and review tasks throughout this study. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Research on the Impact of Actual Tax Bearing Rate on the Financial Performance of Enterprises

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This paper is based on financial data analysis of 241 listed pharmaceutical manufacturing enterprises in China, we study the different effects of different tax reduction policies on the financial performance of enterprises in the short term and long term. Through the verification of practical examples, it could be found that the implementation of a tax reduction policy can indeed play a positive role in the financial performance of enterprises, and the reduction of income tax significantly improves the short-term financial performance of enterprises. However, the tax reduction of turnover tax significantly enhances the long-term financial performance of enterprises, and the effect of tax reduction on the financial performance of state-owned enterprises is better than that of non-state-owned enterprises. Generally speaking, tax reduction policy has a better effect on the financial performance of non-state-owned enterprises and enterprises in central and western regions than state-owned enterprises and enterprises in eastern regions.

Keywords: actual tax bearing rate, pharmaceutical industry, financial performance, financial, non-state-owned

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INTRODUCTION

Research Background and Significance

At the end of 2019, COVID-19 began to spread in China. With the rapid response of the central government and appropriate measures, the epidemic has been contained. However, due to the impact of COVID-19, most of the enterprises has delayed the resumption of work, which lead to severe damage to the profits of many enterprises, even bankruptcy. Therefore, in order to reduce the losses suffered by enterprises as much as possible and help enterprises to get through the difficulties, the state has introduced a series of tax reductions and fee reduction policies. On March 3, 2020, Premier Li Keqiang presided over the executive meeting of the State Council and deployed the "six stable" work coordination mechanism, which decided to increase the intensity of tax reduction and fee reduction. On the same day, at the press conference of the joint defense mechanism of the State Council, director general Fu Jinling of the social security department of the Ministry of Finance introduced that this year's social insurance premium would reduce tax bearing for enterprises by more than 1 trillion yuan.

In this instant tax reduction policy, the government distinguishes the types and scales of different enterprises and take short-term emergency policies from the two various aspects of value-added tax and enterprise income tax. In fact, since the world financial crisis in 2008, in order to alleviate the impact of the financial crisis, maintain the regular operation and production of enterprises, stabilize the employment rate and maintain the growth rate of economic development, the Chinese government has been implementing tax reduction as an essential and effective policy.

From "structural tax reduction" to "inclusive tax reduction," more and more enterprises enjoy the dividend brought by the policy. As shown in **Table 1**, the main tax reduction policies since 2008 have been sorted out, from which it can be seen that the corresponding policies issued by the Chinese government on tax reduction are more and more frequent, powerful, and extensive.

In the past ten years, the tax reduction policy has been implemented more and more comprehensively and deeply in China. This policy is not only an important measure of "supply-side reform," but also a massive push for enterprises to continuously "reduce costs" and "make up for shortcomings." So, what is the effect of the implementation, and what is the role of different tax reduction policies?

According to the previous literature, the main limitations of the research are as follows: First, at present, most articles mainly study equipment manufacturing industry, logistics industry, construction industry and other industries, and there are few literatures analyzing from the perspective of medical manufacturing industry; Second, in most of the literature, the tax categories selected for the study of tax reduction policies are relatively single, and mainly involve in the value-added tax reform, while the impact of different taxes is still relatively small; Thirdly, in many pieces of literature, the evaluation of the financial performance of enterprises start from short-term financial performance, but seldom combined short-term and long-term financial performance for analysis.

The innovation of this research lies in: First, A-share listed pharmaceutical manufacturing enterprises are selected as the research object; second, the impact of actual tax bearing rate of income tax and actual tax bearing rate of a turnover tax on financial performance is comprehensively compared; third, the analysis of financial performance is carried out by selecting different indicators to measure by distinguishing short-term and production period.

The significance of this study lies in: First, through the research of pharmaceutical manufacturing enterprises, we can know the actual effect of tax reduction policy on the pharmaceutical industry operation and enterprise operation and production, which will help policy-makers better grasp the direction of their policies; second, through the analysis of the specific impact of different tax reduction policies, we can know the different effects brought about by different policy tools, which will be beneficial to policymakers; third, through the research on the short-term and long-term performance of financial performance, we can make financial arrangements for decision-makers to make better use of policy benefits.

Literature Review

At present, a large number of studies have focused on the impact of tax reduction on the financial performance of enterprises, but the conclusions of these studies are not uniform. In the view of some scholars, tax reduction has a significant role in promoting financial performance, while some scholars believe that there are differences in the effect of different tax reductions:

Caixia (1) select a sample of A-share listed companies in Shanghai and Shenzhen stock market and show empirically that the higher the cost of corporate income tax, the weaker the profitability (ROE) of the company; Chang et al. (2) take A-share listed companies of Shanghai Stock Exchange and A-share listed companies of Shenzhen Stock Exchange as samples, they use the actual tax bearing rate to measure the tax burden, and conclude that the tax burden has a significant negative correlation with the financial performance (ROE); Meiling (3) chooses A-share listed companies in Shanghai and Shenzhen stock markets for research, the results show that the tax burden is significantly negatively correlated with financial performance (ROA); Jun (4) combines case study and empirical study to research the impact of fiscal and tax subsidies on BYD's financial performance (ROA), and finds that income tax incentives can effectively improve financial performance; Xi (5) conducts an empirical analysis on the real estate development industry, and the research finds that "business tax to value-added tax" opening up the upstream and downstream deduction chain of the industry, which is conducive to the reduction of tax bearing of enterprises, thus improving the financial performance (ROE and ROA) of enterprises; Xiulian (6) establishes a regression model by using panel data of the real estate industry, according to his research results, it can be found that "business tax to value-added tax" has an impact on financial. Ran (7) studies the listed companies of the high-tech service industry, and the results show that the "business tax to value-added tax" improving the financial performance (ROE) by using the PSM-DID method; Qiping (8) studies the situation of high-tech enterprises after "business tax changed to value-added tax" by using the DID method, the results show that the advantages formed by the detailed division of labor promote financial performance (ROE) improved significantly; Chunke (9) researches a total of 50 enterprises listed on the Shanghai Stock Exchange, and the results show that "business tax to value-added tax" has a significant impact on the financial performance of enterprises performance (operating profit, asset-liability ratio and asset turnover ratio) have an increasing role; Yumei et al. (10) study the panel data of listed real estate companies and find that after "business tax changed to value-added tax," financial performance (ROE) has indeed improved; Nafei and Lin (11) conduct a study based on the data of 31 listed agricultural companies by using multiple regression model, the research show that tax preference has an effect on the financial performance of agricultural listed companies performance (ROA) has a significant positive impact.

In addition, some scholars find that after the implementation of the tax reduction policy, the impact on the financial performance of enterprises is not obvious, or even has a negative impact. In some industries, the financial performance is gradually picking up after a certain number of years:

Yupin and Rui (12) conduct a study on logistics enterprises in Shanghai and Shenzhen stock markets, after the "business tax changed to value-added tax," the overall tax bearing decreases, in logistics enterprises, the financial performance (ROE) decreases due to the general over investment in fixed assets; Yongqing (13) finds that "business tax changed to value-added tax" has an impact on the financial performance of modern service industry, performance (ROE) shows adverse effects in the same year, but improves year by year with the promotion of reform; Xiaoshuang (14) takes tourism companies as the research object,

TABLE 1 | Major tax reduction in recent years.

Year	Region	Main measures
2008		First proposed “structural tax reduction”, 15 percent income tax rate shall be applied to enterprises that have obtained the “high-tech enterprise certificate”.
2009	Some regions	Start to implement structural tax reduction and “value-added tax transformation”.
2010	Some regions	Continue the implementation of the transformation reform of value-added tax, and the promotion of the reform of resource tax, etc.
2011	Some regions	Continue the implementation of structural tax reduction policies, the increment in personal income tax deductions from salaries and wages, continue the reduction import tariffs on certain commodities, increment in the threshold for value-added tax and business tax, and the implementation of preferential income tax policies for some small and small-profit enterprises, carried out trials in Shanghai to replace business tax with value-added tax in the transportation industry and some modern service industries.
2012	Some regions	Steady progress is made in piloting the change of business tax to value-added tax, continue to increase the value-added tax and threshold for business tax, and implement preferential income tax policies for small and micro enterprises.
2013	Some regions	Acceleration in the trial of “business tax to value-added tax” trials (develop the “business tax to value-added tax” pilot in the transportation industry and some modern service industries), expand the scope of resource tax ad valorem calculation, Expand the scope of additional deductions for research and development expenses, etc.
2014	Whole country	Preferential income tax for small and micro enterprises, simplified VAT levy rate, improve fixed assets to accelerate depreciation.
2015	Whole country	Further expansion in the scope of small and low-profit enterprises that levy 50% of corporate income tax.
2016	Whole country	Fully promote the “change of business tax to value-added tax”, the phased reduction of the social security provident fund rate, and the expansion of the scope of exemption of 18 administrative fees.
2017	Whole country	Continue to promote the “change of business tax to value-added tax”, expand the scope of small and micro enterprises that enjoy preferential corporate income tax, increase the pre-tax deduction ratio for R&D expenses of technology-based SMEs, etc.
2018	Whole country	Reduce VAT rates, unify small-scale taxpayer standards, expand deductions, increase deductions for employee education expenditures, accelerate depreciation of fixed assets, additional deductions for research and development expenses, relax conditions for technology-based enterprises in the start-up period, etc.
2019	Whole country	Personal income tax reform, inclusive tax reduction and exemption policies for small and micro enterprises, deepen VAT reform, reduce social insurance rates, support preferential tax policies for entrepreneurship and innovation, etc.

TABLE 2 | Variables setting.

Type of variable	Variable code	Variable name	Calculation method
Dependent variables	TBQ	Tobin’s Q value	Market value / replacement cost of the company
	ROE	Return on net assets	Net profit / average net assets
	ROA	Return on total assets	Net profit / total assets
Independent variables	etr	Actual tax bearing rate of income tax	Income tax / EBIT actually paid
	ctr	Actual tax bearing rate of turnover tax	(Actual taxes paid—Actual income tax paid) / total assets
Control variables	zczj	Total assets	Total assets at the end of the year
	birth	Enterprise age	2022—year of establishment
	zcmjd	Asset intensity	Net fixed assets / total assets
	chmjd	Inventory density	Net amount of inventory / total assets
	lev	Leverage ratio	Total indebtedness / total assets

and finds that “business tax to value-added tax” would have a negative effect on the financial performance (ROE) of tourism service industry through case analysis; Yudi (15) reveals that after the implementation of “business tax to value-added tax”, the real estate enterprise financial performance (ROE) has declined, which may be due to the fact that real estate enterprises generally do not tend to update fixed assets, resulting in low efficiency of policy utilization; Guojuan (16) conducts an empirical analysis on Listed Companies in the construction industry, and obtains the financial effect of “business tax replacing value-added tax” through multiple linear regression analysis performance (ROA, ROE) has a negative correlation, but in a short period of time, the policy effect has not been clearly reflected, and the impact on non-state-owned listed companies in the construction industry is more significant than the state-owned ones; Dan (17) selects Ningbo Port Co. Ltd. as the sample, due to the reduction of deductible items and the unclear scope of Taxation, etc., it leads to the change of “business tax to value-added tax,” financial performance (ROA, ROE) has declined; Qin and Jing (18) accords to panel data of 74 information technology service companies in Shanghai and Shenzhen stock markets, using the DID method, finds that the financial performance (ROE) of enterprises in the year of “business tax to value-added tax” decline, but gradually pick up over time.

Based on the above literature conclusions, we can see that tax bearing does have a significant impact on the financial performance of enterprises. In the view of most scholars, they all think that tax cuts will bring improvement of financial performance, but a few scholars think that tax cuts cannot play a rapid positive effect in the short term, which need to be verified for a period of time. In the research of tax reduction, most of them is about "business tax to value-added tax," while the research on income tax is relatively less. In terms of the selection of financial performance indicators, most of the researches choose short-term financial performance as their research indicators, while the researches on long-term financial performance indicators of enterprises are particularly rare. However, for the general policy effect, it is difficult to play an obvious effect in a short time. From the national level, the implementation of the policy needs constant exploration and adjustment, while for enterprises, they need to understand and adapt to the policy constantly. Based on this situation, this paper makes a comprehensive study of different tax reduction policies, short-term and long-term financial indicators, and effect lagging items in order to supplement and improve the above deficiencies.

THEORETICAL ANALYSIS AND HYPOTHESIS

From the micro point of view, the tax reduction is actually equivalent to the indirect financial subsidies given by the state to enterprises, which can be used by enterprises to expand production scale, introduce talents, technological innovation and other aspects (19, 20). Through tax reduction, the second optimal allocation of resources can be realized. At the same time, tax activities will generate tax costs and non-tax costs, which will directly affect the cash flow of enterprises, and then affect the decision-making of enterprise leaders. In addition, at the macro level, the implementation of a tax reduction policy can reflect the continuous reform of the state's tax system, which has a huge role in promoting the optimization and adjustment of industrial structure and the transformation and upgrading of economic development momentum (21–23).

As shown in **Figure 1**, from the perspective of its mechanism, the implementation of tax reduction policy is mainly focused on the government's targeted tax relief for key industries and fields to a certain extent, which reduces the tax burden of enterprises, increases the net profit and total profit, and expands the cash flow of enterprises. Therefore, the enterprise decision-makers can use it in all aspects of production and operation, so as to improve the overall financial situation of the enterprise. There are three main ways for tax reduction to improve enterprise performance: First, the reduction of income tax can reduce the cost of capital of enterprises, thus encouraging enterprises to increase production investment and research and development, thus promoting productivity improvement; Second, after the reduction of income tax, the take-home profits of enterprises will increase, and more cash will be available for production investment and research and development (24). Third, the reduction of income tax means that the after-tax income of unit input is rising, which will produce good social benefits and benefit the development of enterprises. The effect mechanism of turnover tax reduction and income tax reduction on enterprise performance is basically the same, but income tax enterprises generally cannot be transferred, while turnover tax can be transferred (25, 26).

From the perspective of influencing factors, there are four main aspects that will affect the financial performance of enterprises: First, the disclosure of corporate social responsibility, Subin and Yuan (27) and Wenjie (28) find that corporate social responsibility disclosure and financial performance have a promoting relationship; Second, the political connection of enterprises, Chuan et al. (29) shows that corporate political connections can promote financial performance; Third, technological innovation, Xuan et al. (30) find that in the pharmaceutical industry, technological innovation has a significant role in promoting financial performance. Naiping et al. (31) believe that technological innovation would have a positive impact on the short-term and long-term financial performance of enterprises; Fourth, the corporate governance structure, Chenggang et al. (32) studies the data of listed companies through empirical methods, the result shows that the quality of corporate treatment structure has a promoting effect on financial performance, and there is no significant difference between state-owned enterprises and non-state-owned enterprises.

Considering the time value of enterprise development, this paper attempts to analyze the different situations of financial performance in the short term and long term. In the short term, for the enterprises enjoying the tax reduction policy, their cash flow will increase immediately, which will play a significant buffer role for those enterprises with financing problems. Enterprises can make use of the increased cash flow input through tax reduction policies in all aspects of enterprise production and operation, such as increasing investment and improving the weakness of enterprise shortage. These measures will promote the performance of the financial performance of enterprises. In the long run, we can make corresponding conjectures according to the theory of signal transmission. As the government has adopted tax reduction policies for enterprises, it will make investors more confident to invest so as to alleviate the financing problems faced by enterprises to a certain extent. In particular, the continuation of the government's tax reduction policy will probably keep this kind of investment experience, so as to provide cash flow for the sustainable development of enterprises, and thus improve the long-term financial performance of enterprises. In addition, because the design principles of different taxes are different, we speculate that the specific impact of different taxes on financial performance is also different. Income tax is levied on the consequences of the end of the transaction because the enterprise is the ultimate undertaker, so they cannot pass on this tax, directly reduce the cash flow of the enterprise, and reduce the profitability of the enterprise. Commodity turnover tax is a kind of tax levied on the behavior of commodity market transactions. Although the tax will also reduce the cash flow of enterprises, the transaction does not end. Enterprises can transfer the commodity turnover tax as a part of production cost to consumers in a certain proportion, so the impact of commodity turnover tax on enterprises is weakened. Therefore, the commerce turnover tax levies the transaction behavior, while the income tax levies the transaction result income, which has a different influence on the financial performance of the enterprise. Therefore, the preferential benefits obtained in the income tax can all affect the enterprise itself, and because of the transferability of the commodity turnover tax, the preferential benefits brought by the commodity turnover tax will be enjoyed by both the enterprise and the consumer, but the proportion of the two parties is different, and the size of this proportion is mainly determined by the elasticity of commodity demand. We make the following hypothesis:

Hypothesis 1: Income tax reduction is more conducive to the improvement of short-term financial performance;
Hypothesis 2: Compared with short-term financial performance, turnover tax reduction policy is more beneficial to improve long-term financial performance of enterprises.

For enterprises with different types of ownership, there may also be inconsistencies in the implementation of tax reduction policies. First, due to the influence of traditional Chinese concepts. For state-owned enterprises, because of their status as state-owned enterprises, more and more high-end talents will choose to work in state-owned enterprises, which leads to the overall quality of financial staff in state-owned enterprises is better than that in non-state-owned enterprises; Second, compared with other enterprises, state-owned enterprises will be more strict and standardized in government guidance, so financial management business is more scientific and effective than non-state-owned enterprises; Third, because the financial strength of state-owned enterprises is relatively stronger in general, they will be more likely to actively use modern science and technology to strengthen financial supervision and optimize financial workflow.

China has a vast territory, and there are distinct regional differences in economic development. Due to policy factors, factor endowments, regional factors, infrastructure and other factors, China finally shows regional differences in economic development. Compared with the central and western regions, the eastern region has a better business environment for enterprises, with advantages in geographical location, human resources, economic strength, openness and national policies. Furthermore, resource-based theory represented by Penrose believes that an enterprise can be regarded as a collection of various resources under the management framework, and the efficiency of an enterprise is jointly determined by the investment in resources and the management of resources. Due to a long history of inherent deficiency in economic development level and other aspects in the Midwestern China, these may lead to mismatch between the capability of management in companies' resources and the strength of investment in resources, and it is difficult to coordinate resources of information and human. Therefore, the Midwestern China is more responsive and effective to the tax statutory deduction.

For the above reasons, we propose the following hypothesis:

Hypothesis 3: Tax reduction policy has a better effect on the financial performance of non-state-owned enterprises than state-owned enterprises;
Hypothesis 4: Tax reduction policy plays a more significant role in promoting the financial performance of enterprises in central and western Regions.

EMPIRICAL ANALYSIS

Data Sources

Pharmaceutical manufacturing industry is a key industry related to national livelihood. "Made in China 2025" takes the development of pharmaceutical industry as a key content. As an important force of public health security, it is of great practical significance to analyze the impact of tax reduction policies on their financial performance. In this paper, we select the data of 241 A-share listed pharmaceutical manufacturing enterprise from 2008 to 2020 after filtering some samples. The data are obtained from CSMAR and WIND. The main reasons for choosing the data of listed companies as the research object are as follows: First, the development of listed companies is relatively mature, and the financial system is relatively complete; second, due to its open and transparent data in all aspects, data indicators are relatively comprehensive and reliable, and data acquisition is relatively easy. In order to avoid the impact of information disclosure on the results of empirical research, this study selects data according to the following original: (1) Remove all ST Companies in 2008–2020; (2) Remove companies with incomplete data and incomplete data; (3) Remove samples with annual income tax and commodity turnover tax <0; (4) Use the method of tail reduction to remove 1% of the value at both ends of each index.

Variables Setting

Dependent Variable

As shown in **Table 2**, in the aspect of the financial performance of enterprises, in order to better reflect the effect of tax reduction on the financial performance of enterprises in time, financial performance is divided into short-term and long-term financial performance in this study. According to the experience of most papers, ROE is used to express short-term financial performance, and Tobin's Q value is selected to express long-term financial performance.

The reason why the return on net assets is chosen to express the short-term financial performance is that the most important position of enterprise operation is profit, and the maximization of profit is the best embodiment of the effectiveness of the company's financial management. Therefore, we can use the return on net assets to reflect the above purpose. In addition, in many studies, the return on equity is used as the most comprehensive indicator, which can comprehensively measure the financial performance of different enterprises.

The reason why Tobin's Q value is selected is to use it to express long-term financial performance because this indicator is generally obtained by the ratio of the market value of the company to its own replacement cost, which can well measure the future development trend of the enterprise to a certain extent. Compared with the short-term financial indicators, Tobin's Q value is not easy to be manipulated by the enterprise itself. It can

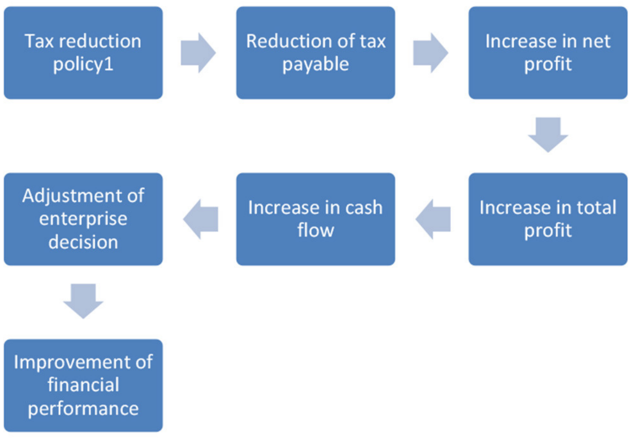

FIGURE 1 | Mechanism of tax reduction.

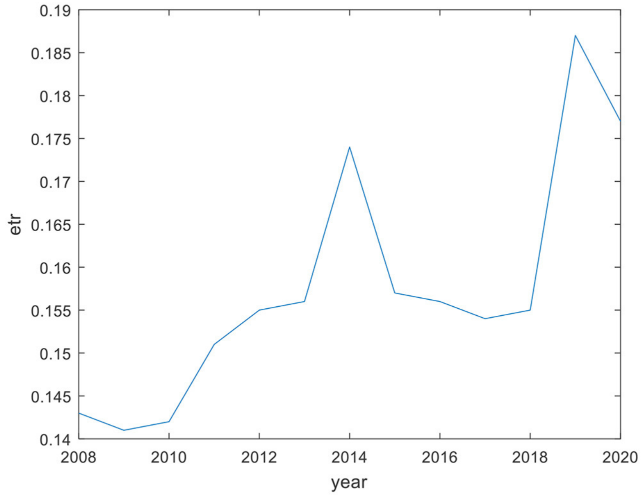

FIGURE 2 | Actual tax bearing rate of income tax (2008–2020).

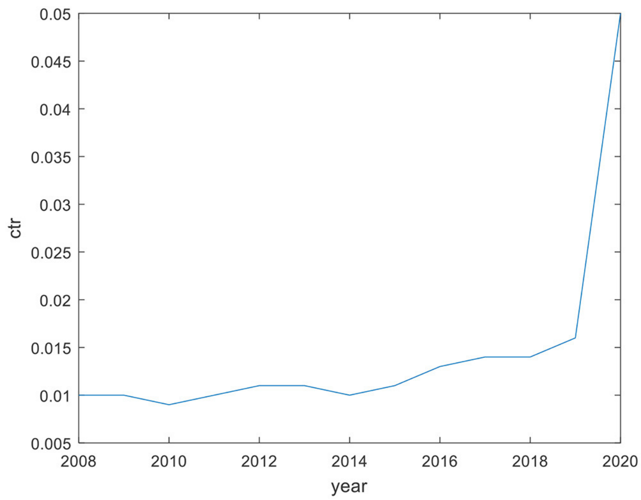

FIGURE 3 | Actual tax bearing rate of commodity turnover tax (2008–2020).

not only predict the future cash flow of the enterprise but also integrate the market value and profitability to reflect the financial performance of the enterprise.

Independent Variables

Based on the experience of most articles, in this paper, the actual tax bearing rate (etr) of corporate income tax and the actual tax bearing rate (ctr) of commodity turnover tax are taken as independent variables. It can be found that the lower the tax bearing rate is, the greater the tax reduction effort and the greater the preferential range of tax.

(1) The actual tax bearing rate (etr) of income tax reflects the real degree of the income tax preference enjoyed by the enterprise itself. The lower the actual tax bearing, the deeper the discount. In the research of this paper, the actual tax bearing rate of income tax is obtained by comparing the total amount of income tax actually paid by the enterprise with the total amount of profit before interest and tax of that year.

(2) For the actual tax bearing rate (ctr) of the commodity turnover tax, the enterprise business tax, and surcharges are used to represent the total amount of the commodity turnover tax, and then the ratio of the total business income is obtained. In this paper, the second method is used to calculate the turnover tax (ctr).

It can be seen from **Figures 2**, **3** that in the first 5 years, on the whole, the actual tax bearing rate of income tax has increased to a certain extent, but it is far lower than the statutory income tax rate of 25%. The actual tax bearing rate of turnover tax is stable on the whole, and is below 2% in all years except 2020, which may be affected by COVID-19.

Control Variables

Referring to the literature published by Chang and Yiling (2), Weibao (33), Qing (34) and other scholars, the following control variables are selected in this paper: Enterprise size (zczj), the size of an enterprise may produce scale effects; Leverage ratio (lev), the higher the asset-liability ratio, the greater the financial leverage effect; Asset intensity (zcmjd), the higher the intensity of the asset, the relative profits will be averaged out and therefore the smaller the profits will be; Inventory intensity (chmjd), inventory intensity directly affects the management cost of enterprises; Enterprise age (birth), the longer the enterprise is established, the more abundant the manpower, material resources and financial resources.

Model of Measurement

Considering that there will be some impacts that do not change with time on the dependent variables, we establish the following two individual fixed effect regression models to analyze the possible impact of tax reduction policies on the financial performance of enterprises:

$$ROE_{it}=\beta_0+\beta_1 etr_{it}+\beta_2 ctr_{it}+\beta_3 X_{it}+\tau_i+u_{it} \tag{1}$$

$$TBQ_{it}=\beta_0+\beta_1 etr_{it}+\beta_2 ctr_{it}+\beta_3 X_{it}+\tau_i+u_{it} \tag{2}$$

In the first model, we test the possible impact of the actual tax bearing rate of income tax and the actual tax bearing rate of commodity turnover tax on the short-term financial performance return on net assets of enterprises. In the second model, it is used to test the possible impact of different tax cuts on the long-term financial performance of enterprises.

Regression Analysis

Descriptive Analysis

Table 3 describes the mean, standard error, minimum and maximum values of each indicator in the sample. In order to avoid possible heteroscedasticity, the total value of assets and the age of the enterprise are logarithmic. It can be seen from the table that the average ROE is 0.14, the overall level is not high, and the difference between the maximum value and the minimum value is small, indicating that the difference between the ROE of the sample enterprises is small. The average value of TBQ is 2.63, indicating that the market value of different enterprises varies greatly. The value range of etr and ctr varies greatly, indicating that the difference of actual tax bearing rate of income tax and actual tax bearing rate of turnover tax is prominent among different enterprises.

TABLE 3 | Description of variables.

	(1)	(2)	(3)	(4)	(5)
Variables	**N**	**Mean**	**SD**	**Min**	**Max**
ROE	2,325	0.146	0.129	0.000	1.986
TBQ	2,092	2.633	1.820	0.761	22.572
etr	1,999	0.160	0.184	0.000	6.824
ctr	2,157	0.0166	0.164	0.000	6.986
lev	2,160	0.321	0.202	0.008	1.893
zcmjd	2,159	0.217	0.117	0.007	0.863
chmjd	2,160	0.118	0.0981	0.003	0.719
lnzczj	2,160	21.74	0.972	19.21	25.15
lnbirth	3,316	2.667	0.486	0.693	3.689

Correlation Analysis

Table 4 shows the degree of correlation between each variable. It can be seen from the table that the absolute values of correlation coefficients between the two independent variables and the four control variables are far <0.4, and the VIF values calculated are all <2. Therefore, the multicollinearity problem between the independent variables and the control variables can be excluded. In addition, ROE has a significant negative linear correlation with etr, lnbirth, lev, zcmjd and chmjd. TBQ had significant negative linear correlation with lnzczj, lev, zcmjd, and positive linear correlation with lnbirth?

Regression Analysis

Hausman test of fixed effects and random effects was conducted on models (1) and (2), and the test results rejected the null hypothesis, indicating that the fixed effects model should be adopted. As can be seen from **Table 5**, the actual tax bearing rate of income tax is negatively and significantly correlated with short-term financial performance, and positively but not significantly correlated with the actual tax bearing rate of turnover tax, indicating that income tax reduction can significantly promote the improvement of short-term financial performance of enterprises, while the relationship between turnover tax and short-term financial performance of enterprises is not obvious. The actual tax bearing rate of turnover tax is significantly negatively correlated with the long-term financial performance of enterprises, while the actual tax bearing rate of income tax is not significantly correlated with the long-term financial performance of enterprises. After the addition of control variables, the above conclusion is still valid, so the hypothesis 1 and the hypothesis 2 are verified. In addition, enterprise size has a significant positive effect on short-term performance, but is not conducive to the improvement of long-term financial performance. The longer the enterprise is established, it has a significant promoting effect on long-term financial performance. Leverage ratio has a significant effect on short-term financial performance, but not on long-term financial performance.

TABLE 4 | Correlation of variables.

	ROE	**TBQ**	**ETR**	**CTR**	**lnzczj**	**lnbirth**	**lev**	**zcmjd**	**chmjd**
ROE	1								
TBQ	0.319***	1							
etr	−0.067***	−0.00700	1						
ctr	−0.0260	−0.0100	0.088***	1					
lnzczj	0.0280	−0.168***	0.0340	−0.0130	1				
lnbirth	−0.222***	0.082***	0.084***	−0.00400	0.336***	1			
lev	−0.065***	−0.138***	−0.0130	0.0200	0.183***	0.129***	1		
zcmjd	−0.140***	−0.070***	−0.0300	−0.0190	−0.134***	−0.0150	0.262***	1	
chmjd	−0.039*	−0.00400	0.00200	−0.0210	0.052**	0.056***	0.263***	−0.051**	1

t-statistics in parentheses.
***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

TABLE 5 | Principal regression result.

	(1)	(2)	(3)	(4)
Variables	**ROE**	**ROE**	**TBQ**	**TBQ**
etr	−0.033***	−0.032***	−0.179	−0.172
	(−2.73)	(−2.59)	(−1.07)	(−1.04)
ctr	0.290	0.287	−13.953**	−18.205***
	(0.84)	(0.80)	(−2.57)	(−3.30)
lnzczj		0.017***		−0.487***
		(2.69)		(−4.94)
lnbirth		−0.015		2.140***
		(−0.54)		(4.90)
lev		0.046**		0.114
		(2.14)		(0.38)
zcmjd		−0.041		−0.115
		(−1.39)		(−0.25)
chmjd		−0.028		1.145**
		(−0.71)		(1.96)
Constant	0.160***	−0.157	1.960***	6.856***
	(15.33)	(−1.10)	(12.55)	(3.06)
id FE	YES	YES	YES	YES
year FE	YES	YES	YES	YES
Observations	1,971	1,956	1,933	1,921
R–squared	0.035	0.046	0.130	0.158
Number of id	254	250	248	244

t-statistics in parentheses.
**** $p < 0.01$, ** $p < 0.05$.*

TABLE 6 | Results of heterogeneous regression of short–term financial performance.

	(1)	(2)	(3)	(4)
Variables	**ROE-s0**	**ROE-s1**	**ROE-a0**	**ROE-a1**
etr	−0.220***	−0.016	−0.325***	−0.017
	(−4.65)	(−1.48)	(−5.20)	(−1.53)
ctr	0.162	2.337**	0.605	0.040
	(0.41)	(2.23)	(0.67)	(0.11)
lnzczj	0.021***	0.026**	0.032**	0.002
	(2.81)	(2.02)	(2.56)	(0.36)
lnbirth	0.013	−0.062	−0.098	0.022
	(0.41)	(−1.01)	(−1.51)	(0.78)
lev	0.054**	−0.027	0.086**	0.041*
	(2.07)	(−0.74)	(2.15)	(1.67)
zcmjd	−0.045	−0.088*	0.057	−0.165***
	(−1.27)	(−1.68)	(1.15)	(−4.58)
chmjd	−0.036	0.053	−0.197***	0.083*
	(−0.82)	(0.63)	(−2.95)	(1.84)
Constant	−0.246	−0.283	−0.233	0.074
	(−1.43)	(−1.05)	(−0.80)	(0.47)
id FE	YES	YES	YES	YES
year FE	YES	YES	YES	YES
Observations	1,507	449	755	1,201
R-squared	0.074	0.067	0.091	0.086
Number of id	209	41	92	158

t-statistics in parentheses.
**** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.*

Heterogeneity Analysis

As can be seen from **Table 6,** income tax reduction has a significant promotion effect on short-term financial performance of non-state-owned enterprises, but not for state-owned enterprises. It has a significant promotion effect on enterprises in the central and western regions, but not for the eastern regions. Turnover tax reduction has no significant promoting effect on non-state-owned enterprises, state-owned enterprises, central and western enterprises and eastern enterprises, and may even have significant negative effect.

As can be seen from **Table 7**, income tax reduction has no significant effect on the long-term financial performance of enterprises in non-state-owned or state-owned, central and western regions or eastern regions. Turnover tax reduction plays a significant role in promoting the long-term financial performance of both non-state-owned and state-owned enterprises, especially for state-owned enterprises. It also plays a significant role in promoting the long-term financial performance of enterprises in central and western regions, but not in the east.

Based on the above analysis, the hypothesis 3 is partially verified and the hypothesis 4 is fully verified. The possible reason why turnover tax reduction plays a greater role in promoting the long-term performance of state-owned enterprises than non-state-owned enterprises is that state-owned enterprises have abundant capital and shoulder important tasks of national economy and people's livelihood. They are not eager to improve short-term financial performance and pay more attention to long-term effects in enterprise development strategy.

Test of Robustness

In order to verify the stability of the results, this paper carries out tests from the following two aspects.

First, the dependent variable was replaced, and return on assets (ROA) was used to replace return on equity (ROE) for regression. Regardless of whether control variables are added, the regression results are consistent and significant with the original regression results.

Second, shorten the data period. Considering that the research object of this paper is the medical manufacturing industry, the tax and fee reduction policies for the manufacturing industry are relatively stable from 2016 to 2020 without major policy changes, so the original data period is shortened to 2016–2020. Regardless of whether control variables are added, the regression results are consistent and significant with the original regression results.

Further Analysis

In the previous analysis, we believed that there was a linear relationship between tax reduction policy and enterprise performance, without considering the possibility of non-linear relationship. Then, we added the quadratic term of tax reduction policy index to conduct regression, and the results are shown in **Table 8**.

TABLE 7 | Results of heterogeneous regression of long–term financial performance.

Variables	(1) TBQ-s0	(2) TBQ-s1	(3) TBQ-a0	(4) TBQ-a1
etr	0.212	−0.224	−0.602	−0.184
	(0.60)	(−1.33)	(−0.77)	(−1.04)
ctr	−12.428**	−65.485***	−52.193***	−8.060
	(−2.03)	(−3.95)	(−4.78)	(−1.21)
lnzczj	−0.507***	−0.634***	−0.556***	−0.467***
	(−4.37)	(−3.07)	(−3.74)	(−3.51)
lnbirth	1.843***	2.178*	3.554***	1.878***
	(3.72)	(1.94)	(4.47)	(3.49)
lev	0.309	−0.736	−0.010	0.297
	(0.87)	(−1.26)	(−0.02)	(0.66)
zcmjd	0.215	−0.654	−0.886	0.460
	(0.40)	(−0.79)	(−1.45)	(0.69)
chmjd	0.901	0.677	1.047	0.886
	(1.35)	(0.51)	(1.32)	(1.06)
Constant	7.818***	10.605**	5.054	7.021**
	(2.93)	(2.33)	(1.41)	(2.35)
id FE	YES	YES	YES	YES
year FE	YES	YES	YES	YES
Observations	1,470	451	748	1,173
R–squared	0.150	0.249	0.230	0.143
Number of id	203	41	91	153

t-statistics in parentheses.
**** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.*

TABLE 8 | Regression results of adding quadratic terms.

Variables	(1) ROE	(2) TBQ	(3) ROE	(4) TBQ
etr	−0.215***	−0.341		
	(−5.65)	(−0.83)		
etr*etr	0.029***	0.025		
	(5.10)	(0.37)		
ctr			1.354**	−27.841***
			(2.13)	(−3.05)
ctr*ctr			−8.483*	83.192
			(−1.89)	(1.23)
Constant	−0.128	7.409***	−0.103	8.890***
	(−0.90)	(3.31)	(−0.73)	(3.39)
Control variables	YES	YES	YES	YES
id FE	YES	YES	YES	YES
year FE	YES	YES	YES	YES
Observations	1,958	1,923	1,988	2,076
R-squared	0.060	0.153	0.041	0.173
Number of id	250	244	250	252

t-statistics in parentheses.
**** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.*

According to the above regression results, after using the U-shaped test, short-term corporate performance is positively U-shaped with the actual tax bearing rate of income tax, while the statistical results show that the number of samples with the actual tax bearing rate of income tax greater than the extreme point is very small (1/1958), which can be ignored. Therefore, it can be considered that there is no non-linear relationship. In addition, by using the same method, we find that the actual tax bearing rate of turnover tax is in an inverted U-shaped with short-term corporate performance. After statistics, we find that the number of samples with the actual tax bearing rate of turnover tax greater than the extreme point is very small (11/1,988), which can be ignored. Therefore, it can be considered that there is no non-linear relationship. Based on the above analysis, we believe that the nonlinear relationship is not tenable.

In addition, OLS is the most commonly used regression method in empirical studies. Standard least squares linear regression only focuses on the influence of E(Y|X). In empirical, however, many researchers on the distribution of Y | X other quantile is also very interested in, so we used quantile regression method, under the actual tax rate at different quantiles of regression, the results as shown in **Table 9**.

As shown in **Table 8**, in OLS regression, income tax reduction can significantly improve short-term corporate performance, while in quantile regression, only when the income tax bearing rate is in the low quantile can it significantly improve short-term financial performance. In OLS regression, turnover tax reduction has a significant improvement effect on long-term corporate performance, while in quantile regression, each sub point of actual turnover tax bearing rate has no significant effect on long-term financial performance. Therefore, we believe that among tax reduction policies, income tax reduction is better.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Based on the research of listed pharmaceutical manufacturing enterprises in China, this paper analyzes the specific impact of tax reduction of different tax types and heterogeneous enterprises on tax reduction policies, and draws the following conclusions:

First, the implementation of tax reduction policies can really play a positive role in the financial performance of enterprises. Due to the differences in the collection principles of different taxes, the impact of varying tax reduction policies on the short-term and long-term financial performance of enterprises will be inconsistent. The reduction of income tax significantly improves the short-term financial performance of enterprises, while the reduction of commodity turnover tax significantly enhances the long-term financial performance of enterprises.

Second, the implementation of tax reduction policy will significantly promote the financial performance of both non-state-owned and state-owned enterprises. Due to the different social status of enterprises with different ownership, tax reduction policy has a better effect on the financial performance of non-state-owned enterprises than state-owned enterprises.

TABLE 9 | Quantile regression results.

Dependent varables	Independent variables	OLS	Quantile regression				
			0.1	0.3	0.5	0.7	0.9
ROE	etr	−0.031**	−0.177*	0.051	0.229	0.011	−0.008
		(−2.57)	(−1.92)	(−0.05)	(−1.12)	(−0.03)	(−0.01)
	ctr	0.365	−0.184	2.674	1.185	1.184	0.363
		(1.06)	(−0.15)	(−0.41)	(−1.61)	(−0.11)	(−0.15)
TBQ	etr	−0.245	−0.59	−0.043	−0.181	−0.082	0.187
		(−1.39)	(−0.65)	(−0.07)	(−0.08)	(−0.02)	(−0.03)
	ctr	−23.676***	0.87	0.254	0.367	3.843	−0.291
		(−4.32)	(−0.14)	(−0.01)	(−0.06)	(−0.07)	(−0.01)

t-statistics in parentheses.
**** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.*

Third, on the whole, enterprise size is beneficial to short-term financial performance, not to long-term financial performance. For enterprises in central and western regions, the promotion effect is significant, but not for enterprises in eastern regions.

Fourth, the establishment time of an enterprise has no significant effect on short-term financial performance, but significantly promotes long-term financial performance.

Fifth, corporate leverage plays a significant role in promoting short-term financial performance, but not in promoting long-term financial performance. Leverage ratio plays a significant role in promoting the short-term financial performance of non-state-owned enterprises, but not for state-owned enterprises.

Recommendations

Based on the above conclusions, we put forward some suggestions as follows:

First, the state should maintain the continuity of tax reduction policy to benefit its positive role better and enable it to play its role continuously.

Second, for some enterprises facing short-term difficulties, the state can make more efforts in the aspect of income tax reduction to help them get through the problems.

Third, for enterprises in the process of sound development, when considering their sustainable development, the state should further explore and deepen the tax reduction policy of turnover tax, so that enterprises can focus on the formulation of long-term development strategy.

Fourth, we need to pay attention to the balance of tax reduction policies between non-state-owned enterprises and state-owned enterprises. Because state-owned enterprises have many advantages such as congenital position, resources, and power, non-state-owned enterprises have their own defects in the process of development. Therefore, the state needs to refine further "structural tax reduction" measures, and combine "inclusive tax reduction" with them, so as to play a better role.

Fifth, the size of the enterprise is not the bigger the better, when the enterprise is large, there may be various risks. The development of enterprises should not only focus on the scale of enterprises, but also control the size of enterprise development, and use more resources to improve the "high quality" development of enterprises.

Sixth, enterprises can maintain a moderate leverage ratio, but to achieve long-term and stable development of enterprises, they should not rely on the leverage ratio. Instead, they should try their best to improve and boost the internal strength and achieve innovation-driven development.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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The impact of network positions in scientific collaboration on pharmaceutical firms' technological innovation performance: Moderating roles of scientific collaboration strength and patent stock

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Scientific knowledge is an underlying basis for technological innovation in the pharmaceutical industry. Collaboration is the main way to participate in the creation of scientific knowledge for pharmaceutical firms. Will network positions in scientific collaboration affect their technological innovation performance? Moreover, what factors moderate the firms' scientific collaboration network positions and technological innovation link? Using a dataset based on 194 Chinese publicly traded pharmaceutical companies, this paper constructs the dynamic scientific collaboration networks among 1,826 organizations by analyzing 4,092 papers included in CNKI and Web of Science databases. Then we probe the impact and boundaries of positions in the scientific collaboration network of pharmaceutical firms on their technological innovation performance through the negative binomial modeling approach. Our study confirms that degree centrality has an inverted U-shaped impact on pharmaceutical firms' technological innovation performance, while structural holes benefit it. Moreover, this article identifies that the strength of scientific collaboration positively moderates the U-shaped relationship between degree centrality and technological innovation of pharmaceutical firms, the matching of high patent stock and high structural holes can promote their technological innovation performance. The results deepen the present understanding of scientific collaboration in the pharmaceutical industry and offer new insights into the formulation of pharmaceutical firms' scientific collaboration strategies.

KEYWORDS

scientific collaboration, degree centrality, structural holes, scientific collaboration strength, patent stock

Introduction

In the era with a highly competitive and increasingly complex environment, a widely used strategy in the pharmaceutical industry is for firms to develop close linkages with universities, research institutes, and industries (URIs) (1). Scientific collaboration, mainly measured by scientific paper co-publication (2), is a common form of those linkages for pharmaceutical firms, where innovation is based on scientific advances (3). Take biopharmaceutical companies in the United States as examples, 116 biopharmaceutical companies published 7,000 papers between 1988 and 1994, among which 70% were published in collaboration with partners like universities and research institutes (4). Chinese pharmaceutical firms also actively participate in scientific collaboration, their co-published papers accounting for 80.76% of the total papers in our sample. Kafouros et al. (2) also noted that Chinese firms rely heavily on scientific collaborations due to their limited internal R&D capabilities. Thus, whether scientific collaboration enhances firms' innovation performance has received substantial interest (5–10). However, there is no agreement on this research topic in the existing literature (2). Some studies revealed that scientific collaboration can increase firms' capacity for problem-solving (2), foster interactive learning (9), and supply a pool of specialized labor (10), enhancing firms' innovation performance. In contrast, other studies argued that it also poses coordination and monitoring challenges due to the cognitive distance (11), divergent incentives, and different targets between firms and URIs (2, 12). To overcome the disagreement, Social Network Analysis (SNA) has been widely adopted in this field recently (3, 8, 13, 14).

From the social network perspective, pharmaceutical firms exchange information, ideas, knowledge, and resources with other actors in complex scientific collaboration networks constructed through scientific collaboration linkages (3). Extant literature has provided valuable insights indicating that actors' characteristics and network attributes were key explanations for pharmaceutical firms' innovation performance (5, 8, 15, 16). Specifically, the number of partners (15), collaboration diversity (5), network breadth, and network strength (8) were conductive to pharmaceutical firms' innovation performance. In addition, some studies investigated the moderating roles of scientific collaboration and firms' innovation links, such as the level of international openness (2), technological dynamics, and market dynamics (8). However, little literature has been focused on the impacts of pharmaceutical firms' network positions in scientific collaboration on their innovation performance and the moderating factors even though some studies have shown that network positions were beneficial to research institutes in their scientific collaboration (13). Meanwhile, the important impact of network positions in technical collaborative networks and strategic alliances on firms' innovation performance has long been the focus of many studies (17–19). Schilling and Phelps (17) proved that firms have greater innovative output when they are engaged in alliance networks of high reach and high clustering. Ahuja (18) posited that firms' direct ties and structural holes in collaboration networks were related to their subsequent innovation output. Wang et al. (19) indicated that network centrality positively influenced organizational innovation, and it was stronger for organizations in knowledge-intensive industries as well as in developed institutional environments. In addition, Yang et al. (8) pointed out that structural holes and network intensity still needed more work, as they were important dimensions of scientific collaboration networks. In this context, some valuable and important topics are worthy of our attention. Do network positions of pharmaceutical firms in scientific collaboration benefit their technological innovation performance? What factors moderate the link between scientific collaboration network positions and pharmaceutical firms' technological innovation?

To fill this gap, we examine how positions in scientific collaboration networks influence the technological innovation performance of pharmaceutical firms from the social network viewpoint. Integrating the framework of SNA and the Knowledge-based view (KBV), we argue that occupying key positions in scientific collaboration networks benefits pharmaceutical firms' technological innovation, and the value of such network positions depends on the strength of scientific collaboration and patent stock, respectively. We propose two typical network positions in scientific collaboration: degree centrality and structural holes, which play different roles in improving the technological innovation performance of pharmaceutical firms. *Degree centrality* has an inverted U-shaped association with technological innovation performance; however, *structural holes* positively enhance it. In addition, we suggest that the value of degree centrality and structural holes depends on scientific collaboration strength and patent stock, respectively: when the strength of scientific collaboration is high, the degree centrality may cause even better results; when the patent stock is richer, more structural holes exert superior and positive effects. To verify our hypotheses, we collected data on 194 Chinese publicly traded pharmaceutical companies during 2005–2021. The dataset involves the information of 4,092 publications by 1,826 organizations included in CNKI and Web of Science databases. The empirical results prove our research hypotheses.

Our study makes three contributions to the literature. First of all, compared with previous research, which mostly neglected firms' network positions in scientific collaboration and mainly focused on the impacts of network attributes and partner characteristics on innovation performance (8, 15), we investigate factors influencing the technological innovation performance of pharmaceutical enterprises in the perspective of network positions, which can offer some important empirical evidence for the influence of scientific collaboration on technological innovation. Furthermore, to provide a more detailed response to the question of how to enhance the value of various network positions in scientific collaboration networks, this research analyzes the moderating variables to the link between network positions and technological innovation performance. Lastly, this paper studies the inter-organizational scientific collaboration in China, enriching empirical research on scientific collaboration in the context of newly industrialized economies, which are fundamentally different from those of the developed countries (2).

Theoretical background and hypotheses

Scientific collaboration and innovation of pharmaceutical firms

The accumulation of scientific knowledge is a prerequisite for technological innovation in the pharmaceutical field. R&D in this industry is generally divided into three stages: government-funded basic research, publication of papers in pharmaceutical journals, and industry-led applied research (20). Research-intensive pharmaceutical firms can accelerate knowledge accumulation that integrates the knowledge of scientists inside and outside to generate valuable technological innovation (4). R&D activities of U.S. pharmaceutical firms increasingly emphasize the use of scientific knowledge generated by scientists at universities, particularly in bioscience-related fields, where inventions approved by the U.S. Food and Drug Administration are positively correlated with scientific publications (21). Sarkissian (22) argued that the top three factors positively influencing drug discovery were highly qualified R&D scientists, R&D investment, and excellent R&D management; the depth of specialized knowledge needed to be taken into account more than the diversity of knowledge available to the discovery teams; however, the main inhibitors to drug discovery were that clinical trials were challenging, the same drug targets were pursued, and drugs were designed with specialized or narrow therapeutic effects.

To date, different levels of research have been conducted on the link between scientific collaboration and innovation of pharmaceutical firms using SNA, including regional/country (3), organizational (2, 5, 8, 14, 15), and individual level (6, 23, 24). At the organizational level, relevant research was mostly focused on the impact of partner characteristics and network attributes in scientific collaboration on innovation performance. Mckelvey and Rake (15) built scientific collaboration networks based on co-publication papers by pharmaceutical firms and found that the number of partners, direct connections with academic institutions, and indirect linkages with academic institutions and biotechnology companies were conducive to pharmaceutical firms' product innovation, but their eigenvector centrality and betweenness centrality in the network had no impact on product innovation. Radicic and Pinto (16) proposed that collaboration between firms and universities and suppliers was conducive to product innovation and process innovation, and cooperation with suppliers was found to raise the tendency of innovation in industries with higher technology intensity; in contrast, collaboration with universities can increase the innovation possibilities in industries with lower technology intensity. Gao and Guan (14) displayed the characteristics of scientific collaboration networks from journals in six fields, e.g., Biotechnology, Pharmaceuticals, etc. to highlight differences in their network structures and identify heavily science-based networks. Lin (5) evaluated university-firm collaborations and found that knowledge stock, collaboration diversity, and collaboration ambition rather than the number of partnerships can lead to higher enterprise performance. In addition, some studies investigated the moderating roles of scientific collaboration and firms' innovation links. Kafouros et al. (2) proved the moderating roles of intellectual property rights enforcement, international openness level, and the research quality of URIs in the emerging market. Yang et al. (8) suggested that market and technological dynamics influenced how the breadth and strength of scientific collaboration networks affected company innovation.

Most of the previous studies recognized that scientific knowledge and scientific collaboration were important to the technological innovation performance of pharmaceutical firms, but mainly from the perspectives of partner's characteristics, network attributes, etc., only meager attention was paid to the relationship between network positions in the scientific collaboration and technological innovation of pharmaceutical firms, and there was also a lack of further discussion of its impact boundaries. In addition, most scientific collaboration networks were constructed from the co-publication papers in the Web of Science database (8). However, publishing papers in English is more difficult for Chinese pharmaceutical firms than publishing Chinese papers. Thus, co-publication in Chinese is the main way to participate in the scientific collaboration for pharmaceutical firms in China. In this context, only focusing on English publications cannot fully capture the actual situation of scientific collaboration networks in the newly industrialized economies. Therefore, we integrate social network theory and knowledge-based theory, take 194 publicly traded pharmaceutical companies as the research sample, and collect Chinese scientific papers published in the CNKI database, which were indexed by SCI, EI, PKU, CSSCI, and CSCD, and English scientific papers in Web of Science databases to build scientific collaboration networks. Using two crucial network measurements—namely, degree centrality and structural holes—we investigate the effects of network positions in scientific collaboration on the technological innovation performance of pharmaceutical companies. And we further explore the moderating role of the strength of scientific collaboration and patent stock on the link between network positions and technological innovation performance.

Network positions and technological innovation performance of pharmaceutical firms

The scientific collaboration network describes the scientific collaboration relationship among various organizations or scientists using coauthored publications data, citation data, etc. (8, 24). In this study, scientific collaboration network refers to collaboration networks formed by pharmaceutical firms, universities, research institutes, hospitals, suppliers, etc. using co-authorship data, which indicate strong social connections (8). According to social network theory, network positions were measured by two typical indicators: degree centrality and structural holes (13).

Degree centrality and pharmaceutical firms' technological innovation performance

Degree centrality refers to the direct links between pharmaceutical firms and other actors, which characterizes pharmaceutical enterprises' centralization in the scientific collaboration network (13, 14). The degree centrality of pharmaceutical firms will be higher if they have more direct links with other partners. In the scientific collaboration network, pharmaceutical firms' degree centrality is conducive to enhancing their technological innovation performance, however, it also comes at a cost. Specifically, degree centrality enhances technological innovation through various mechanisms. First, degree centrality is conducive to knowledge sharing which facilitates bringing together complementary skills from URIs. When all actors collaborate to create new scientific knowledge, the resultant knowledge is available to firms. Therefore, pharmaceutical firms can potentially receive a greater amount of knowledge from scientific collaboration networks compared to that from independent research investment (18). Pharmaceutical firms' partners in scientific collaboration networks are mainly URIs with complementary skills. Under such circumstances, degree centrality can enable firms to tap into the developed competencies of URIs to enhance their knowledge base and improve their innovation performance (25). Second, degree centrality enhances pharmaceutical firms' reputations. In social networks, a higher degree centrality represents a significant impact on partners, which means a great reputation (26). In the process of scientific collaboration, reputation is an important factor in attracting potential partners. With the help of reputation signals, pharmaceutical firms attract outstanding scientific and technological talents and improve their success rate of technological innovation (19). Third, it helps pharmaceutical firms acquire diverse information, a crucial factor to drive technological innovation. Compared to those in the peripheral position, pharmaceutical firms in the central position cover a wider range of the scientific collaboration network (27), and the higher degree centrality is conducive to rapid and effective access to a large amount of cutting-edge scientific information, which increases the scale of firms' technology information pool and avoids information asymmetry in the process of technological innovation (28), which in turn helps firms identify technological opportunities and improve the efficiency of technological innovation. The higher the degree centrality is, the more channels to obtain external information for firms, which can reduce the information search time, decrease the transaction costs between organizations, and avoid falling into path dependence on technological innovation. Mckelvey and Rake (15) also pointed out that the number of pharmaceutical firms' partners in the scientific network has a role in promoting product innovation performance. However, there exist two disadvantages when pharmaceutical firms occupy a high degree centrality in the scientific collaboration network. First, with an increase in the degree centrality, pharmaceutical firms have more ties in scientific collaboration networks, which brings large amounts of information and knowledge, undermining the timeliness and effectiveness of processing information and absorbing knowledge (13). It also may overload pharmaceutical firms, resulting in poor technological performance. Second, reaching and maintaining high centrality increases the cost of collaboration management. It also brings great challenges to firms' absorption capacity due to the cognitive distance between firms and URIs, so it is a great expense for pharmaceutical firms. If pharmaceutical firms fail to absorb the obtained scientific knowledge or integrate it into their existing technical knowledge, it leads to waste (19). Therefore, the technological innovation performance of pharmaceutical firms might be adversely affected by excessively high network centrality.

Given the advantages and shortages of degree centrality, we expect it will exert a nonlinear impact on pharmaceutical firms' technological innovation information. When pharmaceutical firms' degree centrality is at a low level, a higher value of degree centrality is beneficial to them because of more knowledge, high reputation, and diverse information, and enhances their technological innovation performance in the initial stage. However, when a certain point is reached, the benefits brought by degree centrality will be offset by its cost, and thus counterproductive results ensure. Therefore, the following hypothesis is proposed:

> H1: In the scientific collaboration network, pharmaceutical firms' degree centrality has an inverted U-shaped effect on their technological innovation performance.

Structural holes and pharmaceutical firms' technological innovation performance

Structural holes are used to describe such a network structure where two actors concurrently connect with a third actor but do not have direct links with one another, then the third actor acts as a broker (29). As non-redundant links between actors, structural holes can provide their occupants with opportunities to gain information and control benefits, thereby these actors are more competitive than members in other positions in the network. In the scientific collaboration network, pharmaceutical firms can gain three benefits from structural holes. The first is to access heterogeneous information timely. When pharmaceutical firms span more structural holes, which means they build more non-redundant and unique ties to link a large quantity of diverse URIs, they can obtain higher efficiency and more privileges to access heterogeneous information and resources in the network, for example, databases, facilities, and instrumentations (13). It may help pharmaceutical firms to integrate external heterogeneous resources into their innovation processes, so successively generate new ideas and new technologies. Structural holes are also conducive to identifying technological innovation opportunities in time by promoting the dissemination of scientific knowledge and realizing the inter-organizational transfer of scientific knowledge (18). The second benefit is to stimulate pharmaceutical firms' status accumulation. The occupants of structural holes act as brokers in the scientific collaboration network, bringing social capital to themselves (29) and enhancing their status (30). Yan and Guan (31) proposed that structural capital has positive effects on both exploitative and exploratory innovation. The third benefit is to control other nodes in the network and become the tertius gaudens. Structural holes holders have certain control over their partners in the scientific network, which will improve the dependence of the latter on them, reduce the external risk of the spillover of cutting-edge scientific knowledge, enhance the uniqueness of scientific knowledge, and increase the enthusiasm for pharmaceutical firms' R&D investment (13). The second hypothesis is proposed based on the above analysis:

H2: In the scientific collaboration network, the pharmaceutical firms' structural holes have positive effects on their technological innovation performance.

Moderators of network positions and pharmaceutical firms' technological innovation performance link

In the social network analysis, network position indicators focus on nodes in the network, but the strength of ties in the network is not involved. However, previous studies have pointed out that strong ties have a positive impact on technological innovation due to the trust mechanism (6, 8), which can reduce coordination costs in scientific collaboration. Therefore, we propose that the strength of scientific collaboration may affect the link between degree centrality and technological innovation performance. In addition, there is an ancient paradox that has always plagued managers of new products according to the knowledge-based view, that is, how to take advantage of core capacities without being hampered by their dysfunctional pip side (32). Patent stock is the embodiment of the core capabilities of pharmaceutical firms. Meanwhile, structural holes help pharmaceutical firms to gain heterogeneous resources and information. We wonder whether the combination of patent stock and structural holes will be beneficial to the technological innovation of pharmaceutical firms. Thus, our study treats the strength of scientific collaboration and patent stock as moderators of network positions and pharmaceutical firms' technological innovation performance link.

The moderating effects of scientific collaboration strength

The strength of scientific collaboration reflects the closeness of a firm's connection to its partners in a scientific collaboration network, which is measured by the time it lasts and the depth of the relationship (8). Sharing knowledge between pharmaceutical firms and URIs can be more difficult than sharing it within organizations, but the strength of scientific collaboration can facilitate knowledge acquisition, especially that of implicit and complex scientific knowledge by building trust with partners (6). Strong ties in scientific collaboration networks also mitigate the uncertainty associated with innovation (6). Scientific collaboration may entail an idea being openly discussed, being rejected, or even not being given due consideration; therefore, pharmaceutical firms open themselves up to the potential risk of knowledge spillover. When strong ties exist, pharmaceutical firms tend to be more accepting of uncertainty surrounding innovation processes and outcomes. The strength of scientific collaboration is advantageous because of the workings of trust (33). Yang et al. (8) pointed out that scientific collaboration network strength positively affected innovation performance. When the scientific collaboration strength of pharmaceutical firms is high, the degree of mutual trust between them and URIs is high, which will reduce the possibility of conflict in collaboration and decrease the cost of coordination. This is especially important for pharmaceutical firms with a high degree centrality. Although pharmaceutical firms with a higher degree centrality have deep knowledge sharing, higher network status, and richer information, there also face higher coordination costs. Therefore, the scientific collaboration strength will wield positive impacts on the link between degree centrality and the performance of technological innovation, maximizing the benefits obtained from the central position of the scientific collaboration network. Strong ties increase the willingness to share knowledge and reduce the costs of finding the right partner, organizing collaboration, and transferring high-quality information and tacit knowledge (23). Therefore, strong ties help pharmaceutical firms with a high degree centrality to improve the scale and quality of scientific knowledge obtained from URIs and jointly promote technological innovation performance. Tortoriello et al. (34) found evidence that tie strength reduced the negative association between cross-unit transfers and knowledge acquisition. Based on the above discussion, the third hypothesis is proposed:

H3: In the scientific collaboration network, scientific collaboration strength positively moderates the inverted *U*-shaped relationship between degree centrality and technological innovation performance.

The moderating effects of patent stock

Patents are an important part of a company's proprietary knowledge. Patent stock refers to the number of patents owned by a firm in a certain period (35). The size of a firm's patent stock means the extent to which technical knowledge is available. Patent stock can measure the resources that firms invest in technological innovation, and evaluate the quality and technological capabilities of the firm in specific fields, which provides more options to access and recombine knowledge from URIs in the scientific collaboration network (5). Erden et al. (35) pointed out that the patent stock reflected the reputation of firms in the business community and promoted firms' performance. However, when the number of patents accumulates to a certain level, due to the potential core rigidity and path dependence, the patent stock will reduce firms' innovation output, reflecting the accumulation of non-competitive advantages in the process of technological innovation (36). To better tap into the value of structural holes in the scientific collaboration network for the technological innovation performance of pharmaceutical firms, it is also necessary to ensure that pharmaceutical firms can effectively digest, transform and utilize heterogeneous, implicit, and unique scientific knowledge. That the higher patent stock often means that pharmaceutical firms have a huge technological capacity, so the patent stock will strengthen the impact of structural holes in the scientific collaboration network on the performance of technological innovation. In addition, pharmaceutical firms that occupy more structural holes can obtain different scientific research perspectives and new scientific thinking methods from partners, which can help them solve existing technological innovation problems (37), eliminate the negative impact of path dependence and behavior locking, and accumulate core competitive advantages. Specifically, pharmaceutical firms with large patent stocks can better utilize the advantages brought by the structural holes in scientific collaboration networks, screen favorable external knowledge and information from them, integrate existing technical knowledge with scientific knowledge, give play to the supporting role of scientific knowledge in technological innovation, and ensure better innovation performance. Therefore, the fourth hypothesis is proposed:

H4: In the scientific collaboration network, patent stock positively moderates the relationship between structural holes and technological innovation performance.

Combining the above hypotheses, the conceptual framework of the study is shown in Figure 1.

Methodology

Research setting and data collection

In this paper, we verify the four hypotheses in the context of Chinese publicly traded pharmaceutical companies based on the consideration of data availability. Data of 301 pharmaceutical companies were downloaded from the CSMAR database from 2007–2021, and 194 companies were obtained as the final research sample after deleting 107 listed companies that belong to the SSE star market, ST, *ST, SST, S.ST listed companies, and publicly traded companies involved in the pharmaceutical industry <2 years. We initially collected basic information and financial indicators of the sample from the CSMAR database. Secondly, co-publication papers in Chinese were collected from the database of "CNKI Academic Journals." The author's affiliations were the name of sample firms, the search time was 2005–2021, and those papers were indexed by SCI, EI, PKU, CSSCI, and CSCD, which were seen as a sign of better-quality scientific papers in China, and finally, a total of 3,481 Chinese papers were retrieved. Then, English scientific papers were downloaded from the core collection of the Web of Science database. The author's affiliations were searched as names of sample firms, and the search time range was 2005–2021, and a total of 611 English papers were collected. Then, the names of the organizations involved in the paper were carefully proofread, the renamed organizations were merged, and the Chinese and English names of the organizations were examined one by one. Finally, 3,305 co-publishing papers were obtained, involving 1,826 organizations; 2,713 were Chinese papers, and 592 were English papers; the proportion of co-publication in Chinese was 77.94%, and the proportion of co-publication in English was 96.89%. The count results of our data are shown in Figure 2. Furthermore, this paper used 5 years (that is, t-2 to t+2) as the time window to construct 13 scientific cooperation networks following the study of Yang et al. (8). Then we calculated network position indicators of pharmaceutical firms, respectively. Finally,

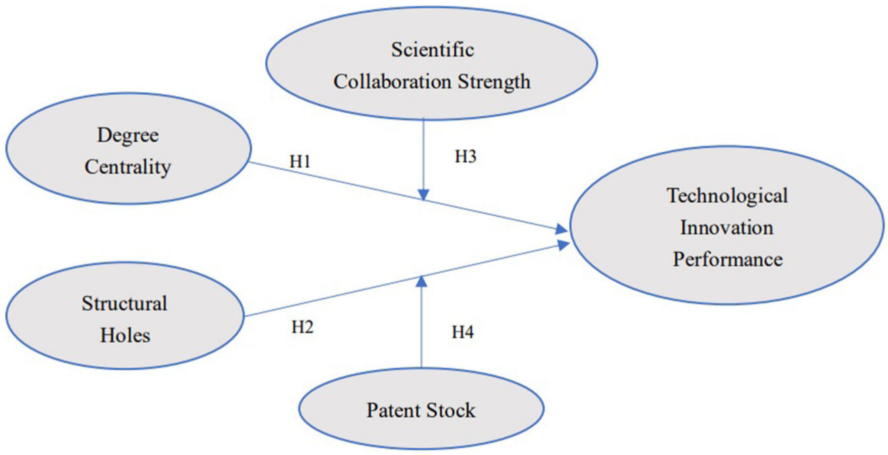

FIGURE 1
Conceptual framework.

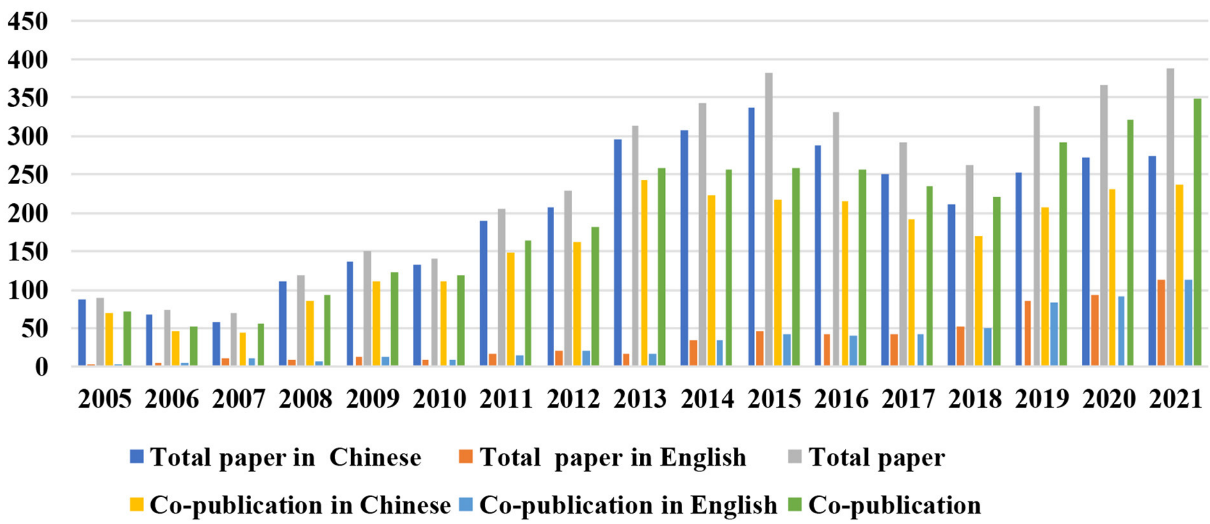

FIGURE 2
The trend of papers published by Chinese publicly traded pharmaceutical companies during the period 2005–2021.

the patent data was obtained from the CNIPA patent search and analysis database in China.

Measures

Dependent variable

Following the previous studies (8, 18), technological innovation performance is measured by the number of innovation patents granted to the firm in years t+1 and t+2 because invention patents are new technical solutions proposed for the method, product, or its improvement, which can better represent the technological innovation level of pharmaceutical firms compared to utility models patents and designs patents in China.

Independent variables

Following Yang et al. (8), and Liang and Liu (38), the scientific collaboration network was constructed by co-authorship in publication data, in which five-year moving windows (t-2 to t+2) were applied.

Degree centrality was measured by the number of direct linkages to the focal node following Chen et al. (13)

and Martin et al. (39). The specific calculation formula is as follows.

$$C_{degree}\left(p_k\right) = \sum_{i=1}^{n} a\left(p_i, p_k\right) \tag{1}$$

where if the node p_i is directly connected to the node p_k, $a\left(p_i, p_k\right) = 1$, otherwise, $a\left(p_i, p_k\right) = 0$, $\sum_{i=1}^{n} a\left(p_i, p_k\right)$ is the number of nodes directly connected to the node p_k, n is the number of nodes in the network.

Structural holes refer to the degree of redundancy in the social network (29). Following Chen et al. (13) and Tortoriello et al. (34), structural holes were calculated using Equation (2).

$$SH_i = 1 - \sum_{j}\left(p_{ij} + \sum_{q \neq i \neq j} p_{iq}p_{qj}\right)^2 \tag{2}$$

where p_{ij} represents the proportion of relations of node i invested in contacting node j in the network. p_{iq} represents the proportion of relations of node i invested in contacting node q. p_{qj} represents the proportion of relations of node q invested in contacting node j. $\sum_{q \neq i \neq j} p_{iq}p_{qj}$ measures indirect dyadic constraint by considering the strength of third-party ties around dyads i and j. The total in parentheses is the proportion of node i's relations that are indirectly or directly invested in the connection with node j.

Moderating variables

Scientific collaboration strength refers to the average number of co-authored papers between focal firms and their partners, which was calculated using Equation (3) following Yang et al. (8).

$$Strength_{it} = \frac{\sum_{t-2}^{t+2} J_{it}}{\sum_{t-2}^{t+2} K_{it}} \tag{3}$$

where J_{it} represents the number of focal firms' co-publications in the time window (t–2 to t+2), K_{it} represents the quantity of distinct partners with which the firm coauthored their publications.

Following Erden et al. (35), the patent stock was measured by the number of invention patents granted to firms before the current year (excluding year t).

Control variables

Following existing studies (8, 18, 21), we controlled for firm attributes. (a) R&D intensity, measured by dividing R&D expense into sales revenue; (b) Size, measured by the logarithm of total assets; (c) Age, measured by the timespan from the establishment of the firm to the current year; (d) SOE, measured by dummy variables where "1" indicates yes and "0" otherwise; (e) R&D subsidy, measured by the logarithm of the sum of the amount of R&D subsidy plus 1; (f) Export, measured by dummy variables where "1" indicates yes and "0" otherwise; (g) ROA, measured by dividing net profit by average total assets, which refers to return on total assets; (h) Leverage, measured by dividing total debt by total assets. In addition, Year was measured by dummy variables from 2008–2019. The region was measured by dummy variables including areas of Central China, Western China, and Northeast China. The industry was measured by dummy variables including chemical pharmacy and traditional Chinese medicine pharmacy.

Model specification and estimates

As the dependent variable technological innovation performance was a count variable, which was overdispersion, we used negative binomial regression models to validate our hypotheses. Since negative binomial regression models can be divided into the fixed-effect model and random-effect model using the panel data, we use the negative binomial model with fixed effects according to the results of the Hausman specification test (40).

Empirical analysis and results

The descriptive statistics and correlations about the main variables in the scientific collaboration network are presented in Table 1. The standard deviations of the dependent variable are greater than its mean; thus, the negative binomial model is appropriate for the research. The mean value of degree centrality is 16.677, and its S.D. value is 47.102, indicating that the degree centrality of pharmaceutical firms in the scientific network is polarizing. Meanwhile, the mean value of structural holes is 0.561, and the value of the standard deviation is 0.321, indicating that structural holes of pharmaceutical firms are more even. As shown in Table 1, the correlation coefficients between the main variables are <0.7, meaning that the discriminant validity is acceptable. The variance inflation factors (VIFs) are all well below the permitted limit of 10, indicating that multicollinearity is not an issue in our model. Moreover, this study standardizes variables including squared terms and interaction terms before regression analysis to avoid the potential multicollinearity issues (41).

Table 2 represents the results of the regression analysis and explains whether our hypotheses hold. Hypothesis H1 predicts that degree centrality has an inverted U-shaped curvilinear relationship with the technological innovation performance of pharmaceutical firms. As Table 2 shows, the linear term of degree centrality is significantly positive ($\beta = 0.152$, $p < 0.05$), while the squared term of degree centrality is significantly negative in Model 2 ($\beta = -0.007$, $p < 0.1$). Hence, the result provides

TABLE 1 Descriptive statistics and correlations about main variables.

Variables	Mean	S.D.	VIF	1	2	3	4	5	6	7	8	9	10	11	12	13
1.Technological innovation performance	5.850	11.791	–	1.000												
2.Degree centrality	16.677	47.102	1.35	0.337***	1.000											
3.Structural holes	0.561	0.321	1.32	0.210***	0.262***	1.000										
4.Patent stock	31.63	58.867	1.54	0.334***	0.395***	0.244***	1.000									
5.Scientific collaboration strength	1.023	0.635	1.08	0.072**	0.068**	−0.131***	0.062**	1.000								
6.R&D intensity	5.537	5.049	1.21	0.064**	0.147***	0.028	0.099***	0.063*	1.000							
7.Size	21.766	0.996	2.60	0.115***	0.208***	0.262***	0.354***	−0.022	−0.050**	1.000						
8.Age	17.534	5.609	1.77	−0.100***	0.085***	0.048*	0.074***	−0.065**	−0.020	0.390***	1.000					
9.SOE	0.263	0.441	1.21	−0.011	−0.041	0.061**	−0.049**	0.080***	−0.184***	0.154***	0.052**	1.000				
10.R&D subsidy	16.253	1.416	2.00	0.108***	0.188***	0.243***	0.295***	−0.014	0.098***	0.644***	0.264***	−0.015	1.000			
11.Export	0.517	0.500	1.25	0.016	0.033	0.047*	0.017	0.029	0.024	0.248***	0.108***	0.051**	0.167***	1.000		
12.ROA	0.069	0.072	1.48	0.151***	0.103***	0.115***	0.028	0.048*	−0.053**	−0.009	−0.074***	−0.079***	0.059**	−0.053**	1.000	
13.Leverage	0.309	0.181	1.68	0.007	−0.021	0.056**	0.104***	0.005	−0.090***	0.270***	0.119***	0.265***	0.188***	0.150***	−0.432***	1.000

*p < 0.1, **p < 0.05, ***p < 0.01.

strong support for H1. The regression result of structural holes is significantly positive in Model 3 ($\beta = 0.095$, $p < 0.05$), indicating that structural holes have a positive impact on firms' technological innovation performance, thus, Hypothesis H2 is proved.

Hypothesis H3 predicts that scientific collaboration strength positively moderates the inverted U-shaped relationship between degree centrality and technological innovation performance. As shown in Table 2, the coefficient of Degree centrality* Scientific collaboration strength is positive and significant ($\beta = 0.290$, $p < 0.05$), and the coefficient of Degree centrality squared* Scientific collaboration strength is significantly negative in Model 5 ($\beta = -0.033$, $p < 0.1$), thus the results support H3. The result is plotted in Figure 3 to clearly illustrate the moderating effect of scientific collaboration strength on the relationship between degree centrality and technological innovation performance. We can see that when scientific collaboration strength is high, the positive slope of degree centrality on technological innovation performance is larger, indicating that scientific collaboration strength enhances the positive effect of degree centrality on technological innovation performance, which supports H3. As shown in Figure 3, the interesting finding is noteworthy: the degree centrality negatively influences technological innovation performance when scientific collaboration strength is low. This indirectly confirms that occupying a higher degree centrality in the scientific collaboration network indicates higher costs.

Hypothesis H4 predicts that patent stock enhances the positive association between structural holes and technological innovation performance. As shown in Table 2, the coefficient of Structural holes * Patent stock is positive and significant in Model 6 ($\beta = 0.177$, $p < 0.05$), hence, the results support H4. The result is plotted in Figure 4 to clearly illustrate the moderating effect of patent stock on the association between structural holes and technological innovation performance. We find that when structural holes are high, the positive slope of structural holes on technological innovation performance is larger, indicating that the positive effect of structural holes on technological innovation performance will be strengthened by patent stock, which supports H4. As shown in Figure 4, when patent stock is low, firms with lower patent stocks have higher innovation performance compared with those with larger patent stocks. The findings of this study are in line with the research of Roper and Hewitt-Dundas (36), indicating the core rigidity of the accumulation of technical knowledge. But our findings go a step further and show that more structural holes in scientific collaborative networks can reverse the negative effects of core rigidity.

We conducted several additional robustness checks. First, considering simultaneous effects of independent variables and moderating variables, we introduce network positions together in Model 4 and incorporate all variables into regression analysis in Model 7. The result shows that the regression results are

TABLE 2 The negative binomial regression for technological innovation performance.

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
R&D intensity	0.009	0.006	0.006	0.005	0.002	0.005	0.002
Size	−0.150*	−0.122	−0.125	−0.131	−0.133	−0.044	−0.034
Age	0.044**	0.073***	0.078***	0.073***	0.080***	0.055**	0.059**
SOE	0.283	0.301	0.311	0.315	0.388*	0.270	0.352
R&D subsidy	−0.013	−0.050	−0.051	−0.054	−0.049	−0.047	−0.044
Export	0.432***	0.359***	0.369***	0.355***	0.271**	0.360***	0.274***
ROA	1.785***	1.515**	1.320**	1.377**	0.900	1.230*	0.823
Leverage	−0.357	−0.118	−0.095	−0.140	−0.216	−0.075	−0.166
Degree centrality		***0.152****		0.136*	0.165*	0.177**	0.228**
Degree centrality squared		***−0.007****		−0.006	−0.020**	−0.007*	−0.029***
Structural holes			***0.095****	0.088*	0.055	0.079*	0.040
Scientific collaboration strength					0.012		0.053
Degree centrality × scientific collaboration strength					***0.290****		0.361**
Degree centrality squared ×Scientific collaboration strength					***-0.033****		−0.047**
Patent stock						−0.414***	−0.477***
Structural holes × Patent stock						***0.177****	0.234***
Constant	3.514**	3.352*	3.360*	3.606**	3.811**	1.829	1.962
Industry	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region	Yes	Yes	Yes	Yes	Yes	Yes	Yes
No. of firms	160	135	135	135	130	135	130
No. of observation	1,161	924	924	924	881	924	881
Log likelihood	−2, 067.830	−1, 743.275	−1, 742.851	−1, 741.334	−1, 646.798	−1, 729.053	−1, 632.492
Prob > chi^2	0.000	0.000	0.000	0.000	0.000	0.000	0.000

*p < 0.1, **p < 0.05, ***p < 0.01. Due to missing data, the number of firms differs across models.

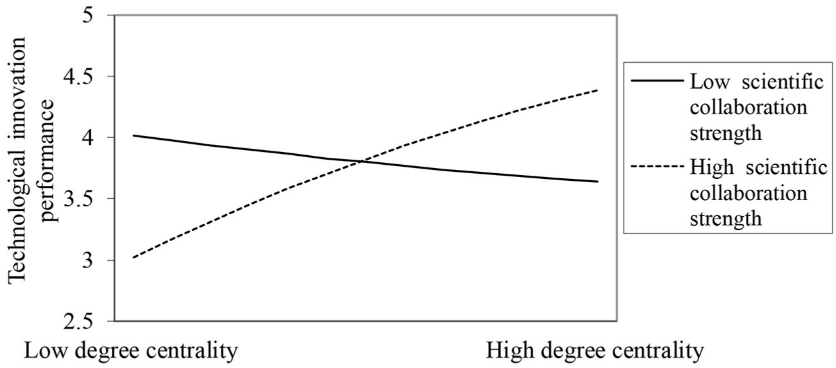

FIGURE 3
The moderating effects of scientific collaboration strength.

reliable. In addition, the Hausman test in our study demonstrates that the negative binomial model with the fixed effect is more appropriate than the model with the random effect for our study. To guarantee robustness, we estimate models with random effects, and we notice that the regression results are robust. Third, using innovation patents granted in *t* year as research outputs, we do a negative regression analysis and discover that the regression results are reliable. Fourth, utilizing lag network positions and moderating variables as research inputs, we analyze negative regression results and find that the regression findings are also robust. In conclusion, our results have a satisfactory level of reliability.

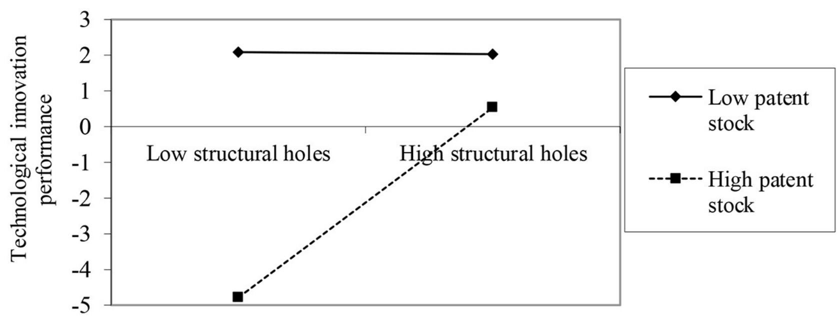

FIGURE 4
The moderating effects of patent stock.

Discussion

Research findings and discussions

The objective of this study is to investigate whether and how Chinese pharmaceutical firms' positions in the scientific collaboration network promote their technological innovation performance. For this purpose, we construct 13 inter-organizational scientific collaboration networks of 194 publicly traded pharmaceutical enterprises in China. We discover that the network positions in scientific collaboration networks of pharmaceutical companies have a considerable impact on their technological innovation performance. Specifically, degree centrality has an inverted *U*-shaped relationship with technological innovation performance, structural holes are positively associated with it. These findings extend the empirical research on the impact of inter-organizational scientific collaboration on pharmaceutical firms' technological innovation performance from a network perspective. Most of the existing literature ignores this research perspective. Moreover, we investigate the contingent roles of scientific collaboration strength and patent stock on the association between network positions in scientific collaboration and technological innovation. Scientific collaboration strength reinforces the positive effect of degree centrality, which conforms to the extant studies that have proven a positive effect of scientific collaboration strength on firm innovation (8). We expand on it and find that when scientific collaboration strength is higher, firms will benefit from a high degree centrality in the scientific collaboration. Patent stock is negatively associated with firm technological innovation, which shows no difference from previous studies (36). However, we prove that when patent stock is high, firms will take advantage of high structural holes in the scientific collaboration network, which develops the empirical studies concerning the core rigidity of the accumulation of technical knowledge.

Implications for theory

This paper makes contributions to the academic debates on scientific collaborations. Even though numerous researchers supported that scientific collaboration is conducive to firm innovation (8, 10), some contended that scientific cooperation did not necessarily facilitate innovation (2, 11). In this paper, we explore whether firms gain from scientific collaboration from a social network viewpoint, and discover that the effects of scientific collaboration on firms' technological innovation performance are impacted by their network positions.

The study also demonstrates the contingent value of scientific collaboration strength and patent stock. Although previous literature has perceived the potential positive effects of strong ties on firm innovation (8), our paper shows that the effects of degree centrality will depend on the strength of scientific collaboration. Though the negative effect of patent stock on technological innovation also has been discussed in previous literature (36), this study proves that the effects of structural holes will be moderated by patent stock. As a result, our paper provides nuances to the existing study on the effects boundaries of different network positions in scientific collaboration.

As Yang et al. (8) noted, most of the prior studies of firm scientific collaboration are based on joint patent applications, and co-authorship networks have not been fully explored. This study makes contributions to the research on the association between scientific research and technological innovation, which is one of the earliest studies concerning the relationship between science and technology in the research field of pharmaceutical firms (4).

We also extend the research on technological innovation of pharmaceutical firms in the newly industrialized economy context. As discussed earlier, the technological innovation of pharmaceutical firms in the newly industrialized economy differs from that of the developed countries (2). However, little research has been devoted to the technological innovation of pharmaceutical firms in China from a social network perspective so far. In our paper, the association between scientific collaboration and technological innovation of Chinese pharmaceutical firms is investigated systematically.

Implications for practice

For firm administrators, our study suggests that enterprises should build a scientific collaboration network and occupy either medium degree centrality or high structural holes to enhance their technological innovation performance. In addition, firms also should be wary of the negative impact of excessive-high degree centrality in scientific collaboration. This study also finds contingent values of scientific collaboration strength and patent stock, which suggests that firms should adjust their network positions in scientific collaboration networks based on their internal conditions. Specifically, when the scientific collaboration strength is high, firms should collaborate with more URI partners to get a high degree centrality in the scientific collaboration network. Given the negative effect of core rigidity in technological knowledge stock, firms should occupy more structural holes to get more heterogeneous scientific knowledge when the patent stock is high.

For government policymakers, this paper argues that they should encourage pharmaceutical firms to research with URIs and occupy key network positions. Meanwhile, governments should urge firms to collaborate with URIs repeatedly and build a relationship of mutual trust, which may better fit a broad scientific collaboration network. In addition, the government may adjust the assessment criteria for pharmaceutical firms so that they will be rewarded for conducting not only patent applications but also related academic paper publications. Given the increasing uncertainty in public health during the COVID-19 period, public policies ought to play more important roles in improving the technological innovation performance of pharmaceutical firms.

Limitations and future research

Although this study investigates the impact and boundaries of positions in the scientific collaboration network of pharmaceutical firms systematically, it has some limitations. First, as Yang et al. (8) noted, co-authored publications have limitations in the field of measuring scientific collaboration. For instance, "hidden" scientific collaborations cannot be captured, such as sharing facilities and data in private and exchanging ideas through meetings. Besides, we focused on papers co-published in CNKI and Web of Science, but academic books and basic research reports are not included, which are also important output information (13). Therefore, it is suggested that future research explore the impact of network positions by integrating publication papers with other sources of data. Second, we only studied two network positions in scientific collaboration networks: degree centrality and structural holes. Other important dimensions, e.g., different brokerage roles and cliques, should be investigated in future studies. In addition, this study only considered the moderating role of scientific collaboration strength and patent stock when exploring the influence boundary of different network positions on technological innovation performance. Future studies can probe other important moderators, such as R&D incentive policies, digital transformation, etc., to get promising and richer research results. Third, following previous studies, this paper selected the number of invention patents granted to firms to measure their technological innovation performance, but patents are only one of the external indicators of technological innovation performance. Future studies can measure it by other important indicators, e.g., sales of new products and the number of new drugs. Finally, this empirical study is limited to publicly traded pharmaceutical companies in China. However, the methods in this paper can be replicated. Future studies can validate our research framework using data from unlisted pharmaceutical firms or pharmaceutical firms in other emerging countries.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

X-XW: design of the research, raw data collation, data analysis and results interpretation, article writing, and revision. H-YJ: part of the raw data collation and article revision. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpubh.2022.980845/full#supplementary-material

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Research on the evolution of the Chinese urban biomedicine innovation network pattern: An analysis using multispatial scales

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This paper addresses the spatial pattern of urban biomedicine innovation networks by separately using four scales, i.e., the national scale, interregional scale, urban agglomeration scale, and provincial scale, on the basis of Chinese biomedicine patent data from the incoPat global patent database (GPD) (2001–2020) and using the method of social network analysis (SNA). Through the research, it is found that (1) on the national scale, the Chinese biomedicine innovation network becomes denser from west to the east as its complexity continuously increases. Its spatial structure takes the form of a radial network pattern with Beijing and Shanghai as its centers. The COVID-19 pandemic has not had an obvious negative impact on this network at present. (2) On the interregional scale, the strength of interregional network ties is greater than that of intraregional network ties. The eastern, central and western biomedicine innovation networks appear to be heterogeneous networks with regional central cities as the cores. (3) At the urban agglomeration scale, the strength of intraurban-agglomeration network ties is greater than that of interurban-agglomeration network ties. The three major urban agglomerations have formed radial spatial patterns with central cities as the hubs. (4) At the provincial scale, the intraprovincial networks have poor connectivity and low internal ties strength, which manifest as core-periphery structures with the provincial capitals as centers. Our research conclusion helps to clarify the current accumulation of technology and offer guidance for the development of China's biomedicine industry.

KEYWORDS

China, urban innovation network, biomedicine, network pattern, patent cooperation, multiscale

Introduction

The outbreak of the COVID-19 pandemic has accelerated the evolution and development of the biomedicine industry. As the "Diamond Industry" of the new century, biomedicine has already become a strategic industry in countries of the world, e.g., the biomedicine industry has been included in the high - end industrial field of national key development in China, and receives focused support by governments (1, 2). In light of the developing situation of the biomedicine industry at home and abroad, this sector favors spatially aggregated distribution, with a significant amount of clustering (3). At present, the Chinese biomedicine industry has taken on the notable characteristics of regional aggregation in the Yangtze River Delta (YRD), Beijing-Tianjin-Hebei (BTH) and Pearl River Delta (PRD) areas. With knowledge and information flowing faster across both individual regions and across the whole world, the biomedicine industry no longer seeks cooperative innovation within an agglomeration only and has rather begun to be characterized by interregional cooperation (4). With the support of policies, the Chinese biomedical industry has developed rapidly, but there are still some problems that restrict the further development of the industry, especially in regional innovation cooperation, which need to be solved. In practice, the means of seizing this opportunity to accelerate Chinese self-innovation in the biomedical industry and to optimize the spatial structure of this industry has become an urgent problem to be solved in postpandemic China.

In addition, since the 1980s, the research perspective regarding contemporary economic geography has shifted from that of "Relationship" to that of "Flow Space," the traditional line mode has been transformed into a network mode, and networking innovation has become the mainstream of innovation research (5). In terms of methodology, most scholars have carried out research efforts on innovation networks by using data related to jointly applied patents and cooperative papers (6–8). With respect to research contents, scholars have conducted research and analysis of innovation networks on the basis of different disciplines and perspectives. In the early stages of this research, scholars studied the concepts and connotations of innovation networks mainly from perspectives such as organizational systems, information covenants, knowledge and skills, and regional space (9–15). To deepen this research, scholars have shifted their focus to the formation process, characteristics and structure of the innovation network using such SNA indices as centrality, structural hole, and network density, using knowledge flow, technological innovation, and industrial agglomeration, etc., as breakthrough points from industry perspectives such as those of bioscience and information technology (16–19).

Over recent years, scholars have generally attached greater importance to the factors influencing the formation of innovation networks, conducting research mainly on the internal structure of the network and its external environment. The internal structure of a network includes the general characteristics of the network, represented by indices such as network scale, and the network formation elements, represented by indices such as small world properties (19–24). Research on the external environment of a network mainly focuses on proximity and the regional environment where the subject is located (25–28).

A general review of the existing research finds that previous research efforts on innovation networks were mostly carried out on a single scale, e.g., the national scale, provincial scale, urban agglomeration scale, urban scale or rural scale (29–31). However, in existing research projects, investigations into urban innovation networks rarely take an urban perspective. Athey et al. (32) pointed out that research on innovation should take cities and the important characteristic of their orientation as basic units, since cities are geographic spaces where innovation subjects are the most active and centralized and are the places with the highest innovation efficiency. As a result, ascertaining the spatial situation of cooperation between Chinese biomedicine and Chinese biomedicine patent data can help to identify problems from a novel point of view and help to better understand China's technological accumulation in the biomedicine field.

The potential contributions of this research are as follows: (1) Taking cities as the basic unit, we assess the biomedical innovation capabilities of Chinese cities and deepen the research on urban innovation networks; (2) The research methods verticalize the original innovation network research perspective, namely, that of multispatial scales, and enrich the theoretical system of innovation geography; (3) Moreover, an in-depth analysis of the evolution of urban biomedicine innovation network patterns from the perspective of different spatial scales, e.g., the national scale, urban agglomeration scale, interregional scale, and provincial scale, will help drive the innovative growth of the Chinese biomedicine industry and offer guidance for the development of China's biomedicine industry.

The rest of this paper is organized as follows: Chapter 2 introduces the research methods and data sources; Chapter 3 analyzes the structure and evolution of China's urban biomedical innovation network from different spatial scales, e.g., the national scale, urban agglomeration scale, interregional scale, and provincial scale. Chapter 4 summarizes the research content and points out the potential contribution and limitations.

Research data and methods

Research data

The data quoted in this paper came from the incoPat GPD. The retrieval year interval spanned from 2001 to 2020, the retrieved objects were Chinese biomedicine patents (excluding

H.K., Macao, and Taiwan), and the retrieval strategy was to require two or more applicants[1] in the patent application, so a total of 37,350 biomedicine patents[2] were selected.

Research methods

In this paper, the SNA method was used to analyze the structural characteristics of Chinese urban biomedicine innovation networks and the evolution of their network patterns. The SNA method is a quantitative analysis method developed on the basis of mathematical methods, graph theory, etc., and it is one of the most widely used research methods in sociology and economics (33).

For our research, we defined overall network structures on four scales, i.e., the national scale, interregional scale, urban agglomeration scale, and provincial scale, by taking Chinese cities as the nodes of the network and the connections between the cities as the edges of the network. On this basis, we quantified the node, edge and overall characteristics of the urban biomedicine innovation network on multiple scales to study the evolution of the Chinese urban biomedicine innovation network pattern.

Structural characteristics of the urban biomedicine innovation network on different spatiotemporal scales

National scale

The Chinese national biomedicine innovation network becomes denser from west to east as its complexity continuously increases

In this paper, the evolution process of the network was divided into four phases, namely, the starting phase (2001–2005), growing phase (2006–2010), expanding phase (2011–2015), and mature phase (2016–2020), according to the cooperative situation of urban biomedicine patents. In addition, the four phases of evolution of the Chinese urban biomedicine innovation network were visualized with ArcGIS software (Figure 1).

Starting phase: The 2001–2005 period is the starting phase of the Chinese national urban biomedicine network (Figure 1A). In this phase, the overall ties among the cities in the network were generally weak, and the network had a low density and a simple structure with a rare closed-loop innovation. In detail, less than one-fifth of the cities were brought into the biomedicine innovation network, with Beijing and Shanghai serving as the cores and Guangzhou and Tianjin as the main nodes. Chongqing, as a municipality controlled directly by the Central Government, did not exhibit an evident impetus toward radiating outwards during this phase. The ties between Beijing and Shanghai, Beijing and Fushun, Beijing and Shenzhen, Shenzhen and Nanjing, and Beijing and Haikou were all close. In terms of region, there were only six cities in the west that participated in the biomedical innovation network.

Growing phase: The 2006–1010 period represents the growing phase of the Chinese national urban biomedicine network (Figure 1B). In this phase, the network nodes increased considerably from those in the first phase, which indicates that there were more cities participating in the Chinese national urban biomedicine innovation network, which was experiencing an evidently expanding network size and a strengthening of the ties among cities. In terms of spatial structure, Beijing and Shanghai functioned as the radiation impetus center, with Nanjing, Guangzhou, Tianjin, Shenzhen, Hangzhou, and Wuhan serving as the main nodes. In detail, the density of the innovation network increased remarkably in the eastern coastal areas but remained at a low level in the west. Beijing and Shanghai continued to be the core cities and to play a radiation impetus role in the network during the growing phase. The ties between Beijing and Fushun and between Beijing and Shenzhen became increasingly close, which slightly differed from those in the starting phase. Meanwhile, some cities in the west were brought into the network, and the ties between the cities in the central region and those in the eastern region increased, with the interregional obstacles between the eastern and central regions gradually began to break down.

Expanding phase: The 2011–1015 period represents the expanding phase of the Chinese national urban biomedicine network (Figure 1C). In this phase, the number of cities participating in the biomedical innovation network increased by nearly 50% from that during the second phase, with the size of the network obviously expanding. The network in this phase exhibited a radial spatial structure with Beijing and Shanghai serving as the main radiation impetus cores and Nanjing, Guangzhou, Wuhan, Shenzhen, Hangzhou, Chengdu and Tianjin serving as the main nodes. The main ties in the network were between Beijing and Shanghai, Beijing and Tianjin, Beijing and Xi'an, Beijing and Jinan, Beijing and Qingdao, and Beijing and Shenzhen.

Mature phase: The 2016–1020 period represents the mature phase of the Chinese national urban biomedicine network (Figure 1D). During this phase, most Chinese cities were brought into the biomedicine innovation network, with both the size and density of the network increasing obviously. Beijing and Shanghai remained the core cities in this phase, and the network density in the west increased robustly. In particular, the radiation impetus abilities of Chengdu, Xi'an

1 In calculating patent cooperation, if a patent is applied for jointly by three patent applicants, i.e., A, B, and C, then cooperations between A and B, between A and C, and between B and C will be calculated separately.

2 The data retrieval date is May 31, 2022.

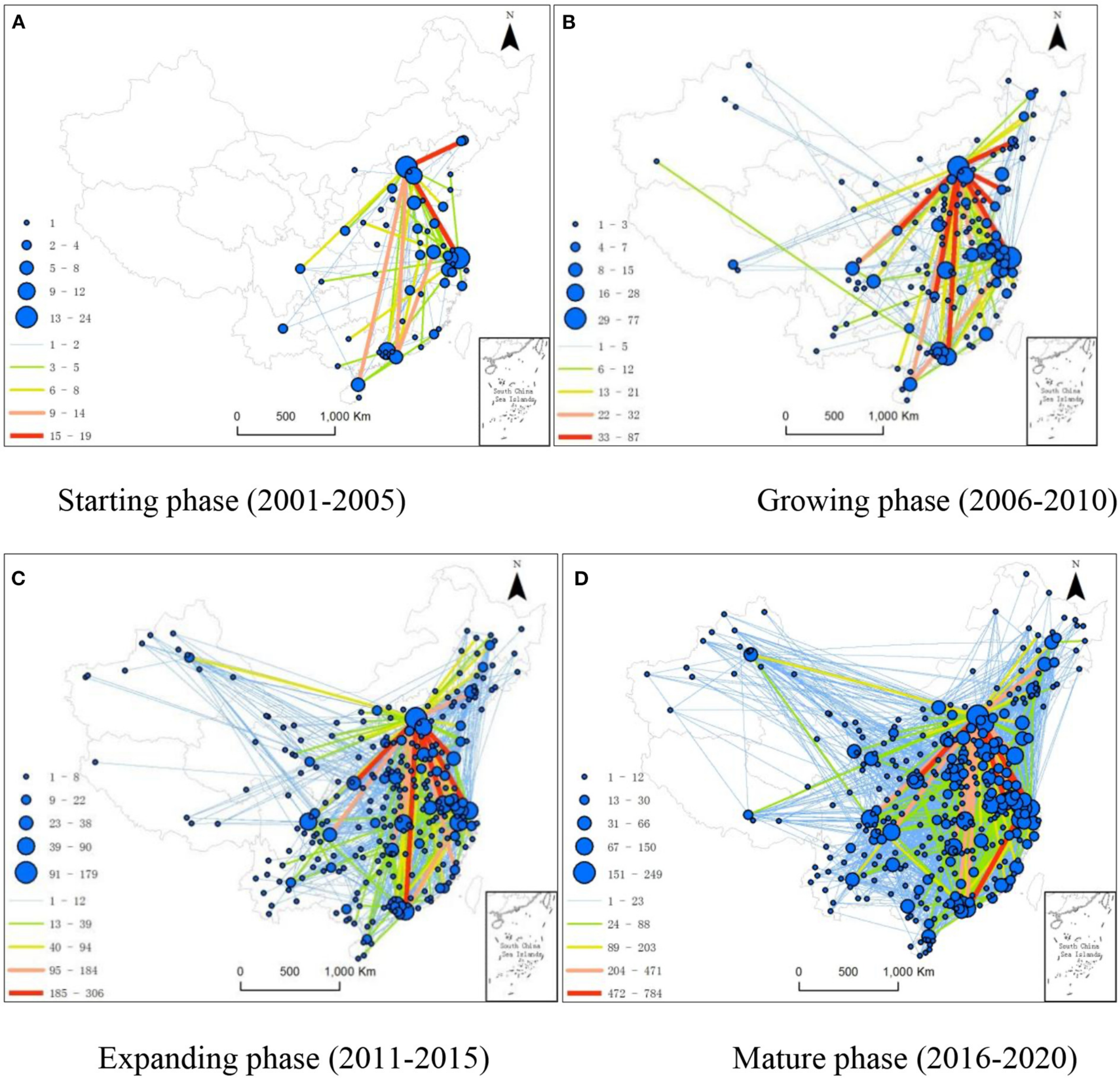

FIGURE 1
Spatiotemporal Evolution of the Chinese National Urban Biomedicine Innovation Network during the time span of 2001–2020. **(A)** Starting phase (2001–2005). **(B)** Growing phase (2006–2010). **(C)** Expanding phase (2011–2015). **(D)** Mature phase (2016–2020).

and Chongqing were enhanced, and Chengdu, Xi'an and Chongqing became the radiation impetus centers in the west, with close ties with the central and eastern regions. The tie strengths between Tianjin and Beijing, Beijing and Nanjing, Beijing and Xi'an, Beijing and Shanghai, Suzhou and Shenzhen, and Lianyungang and Shanghai were obviously strengthened compared with those in the expanding phase. In addition, many closed innovation loops, including Nanjing-Kunming-Baoshan, Beijing-Yulin-Xi'an, and Chongqing-Beijing-Yantai, were developed within the Chinese national urban biomedicine network. Such a closed network spatial structure enabled the flow of knowledge and information within the network to exhibit a self-reinforcing effect, which is helpful for biomedical innovation.

Generally, both the density and size of the Chinese national urban biomedicine innovation network have increased robustly, but the radiation impetus centers and innovation ties are all located in the eastern coastal areas, with the innovation network density becoming obviously lower as one moves west. In detail, Beijing and Shanghai have salient core positions in the innovation network with very strong radiation impetus abilities and the most extensive influence and scope. In all four phases, the innovation network displayed a radial spatial pattern with Beijing and Shanghai as the cores.

Overall ties in biomedicine innovation network strengthened over time, and polarization weakened

The statistical characteristics of the network (see Table 1) were assessed by calculating the nodes, edges, average degree and average weighted degree of the Chinese urban biomedicine innovation network throughout the 2001–2020 period using Gephi. In terms of network size, the numbers of nodes and edges increased from 56 and 88 in the 2001–2005 period to 337 and 2,889 in the 2016–2020 period, respectively, which indicates that in the mature phase, a total of 337 cities were brought into the national urban biomedicine innovation network; in other words, most Chinese cities had been incorporated into the network. In terms of network connectivity, the average degree rose from 3.14 in the 2001–2005 period to 17.15 in the 2016–2020 period, which means that on the national scale, in the mature period, every city had connected with ∼17 other cities with respect to biomedicine patent cooperation, which accounted for ∼5% of the total number of cities, indicating poor network connectivity. In terms of network ties strength, the average number of biomedicine patents related to intercity cooperation increased from 11 in the 2001–2005 period to 208 in the 2016–2020 period.

On the basis of the overall network properties and using hierarchic statistics, the data with tie strengths of >1 and those with tie strengths that were greater than the average were selected to form new networks, and then the nodes, edges, average degrees and average weighted degrees of the networks were calculated separately. When the tie strength was >1, either the number of nodes and edges or the average degree and average weighted degree decreased to a certain extent. However, the extent of such declines differed over time: the extent of the decline in the numbers of nodes and edges dropped from 41.07 and 57.95% in the 2001–2005 period to 10.09 and 25.06% in the 2016–2020 period, respectively. The extent of the decline in the average degree rose from 11.36% in the 2001–2005 period to 25.06% in the 2016–2020 period. This means that during the mature phase, by taking cooperation strength into account, we can see that the number of cities participating in the national biomedicine innovation network decreased by 34, and the intercity cooperation quantity decreased by 5, which is a large drop compared with that across the entire network. 10.09% of cities had an urban biomedicine innovation cooperation quantity of <1. Taking the average tie strength into account, the numbers of nodes and edges and the average degree of the network during the 2001–2005 period were 50.00, 35.23, and 35.22% of those across the entire network, respectively, and the numbers of nodes and edges and the average degree of the network in the 2016–2020 period were 51.04, 16.03, and 16.03% of those across the entire network, respectively. This means that over the 2001–2005 period, the technological cooperation quantity was less than the average in half of the cities, and ∼65% of the biomedicine patent cooperation projects were located in 28 core cities, including Beijing, Shanghai, and Guangzhou, which had a salient polarization effect on the innovation network. In the 2016–2020 period, however, nearly half of the cities had biomedicine innovation cooperation quantities that were lower than the average, and nearly 80% of the patent cooperation projects were located in 172 cities, with the polarization effect within the innovation network greatly weakened.

Generally, the overall ties in the Chinese national urban biomedicine innovation network have been gradually strengthened, the cooperation scope has been somewhat expanded, and the polarization effect of the network has gradually disappeared.

Further discussion: Impact of the COVID-19 pandemic on the biomedicine innovation network

Investigating the Chinese urban biomedicine innovation network before and after the outbreak of the COVID-19 pandemic shows that the pandemic has not had a negative impact on Chinese biomedicine innovation cooperation. In contrast, the numbers of nodes and edges and the centrality and weighted centrality of the network have increased (see Table 2). The number of cities participating in the Chinese urban biomedicine innovation network increased by 19 from 2019 to 2020, with the number of network ties increasing by 298. In terms of network connectivity, the average degree increased from 9.26 in 2019 to 10.61 in 2020, which means that on the national scale, the number of cities cooperating with every other city regarding biomedicine patents increased from 9 to 10, and the network connectivity increased. It can be found from network ties strength that the average quantity of the intercity biomedicine patent cooperation projects rose from 57 in 2019 to 65 in 2020.

Beijing and Shanghai have served as the main Chinese innovation nodes and radiation impetus centers both before and after the outbreak of the COVID-19 pandemic. Qingdao dropped from the top 10 cities, and Xi'an replaced Qingdao and ranked 6th. In addition, among the top 10 nodes, the centrality of Shenzhen dropped from 65 in 2019 to 60, which means that the number of cities cooperating with Shenzhen in patents decreased to 60, while the centralities of other nodes increased to varying degrees. In 2019, the ties between Beijing and Tianjin, Shenzhen and Suzhou, Beijing and Shanghai, Beijing and Nanjing, and Beijing and Wuhan were the main ties in the network. In 2020, the ties between Beijing and Qingdao strengthened, ranking among the top 10.

TABLE 1 Evolution of the statistical characteristics of the Chinese national urban biomedicine innovation network.

	Period	Node	Edge	Average degree	Average weighted degree
Entire network	2001–2005 period	56	88	3.14	11.11
	2006–2010 period	142	315	4.42	30.72
	2011–2015 period	280	1,080	7.71	83.64
	2016–2020 period	337	2,889	17.15	208.62
Ties strength >1	2001–2005 period	33	37	2.79	10.75
	2006–2010 period	89	280	3.94	30.24
	2011–2015 period	217	900	6.43	82.35
	2016–2020 period	303	2,165	12.85	204.33
Ties strength greater than the average	2001–2005 period	28	31	1.11	7.18
	2006–2010 period	55	80	1.13	22.44
	2011–2015 period	124	211	1.51	63.04
	2016–2020 period	172	463	2.75	160.74

The average values of cooperation strength in the 2001–2005 period, 2006–2010 period, 2011–2015 period, and 2016–2020 period were 3.53, 6.94, 10.84, and 12.17, respectively.

TABLE 2 Evolution of statistical characteristics and network patterns of the Chinese national urban biomedicine innovation network.

	2019	2020
Number of nodes	293	312
Number of edges	1,357	1,655
Centrality	9.26	10.61
Weighted centrality	57.07	65.61
Node (centrality)	Beijing (155) Shanghai (88) Nanjing (72) Wuhan (70) Guangzhou (70) Shenzhen (65) Chengdu (61) Hangzhou (58) Tianjin (55) Qingdao (54)	Beijing (179) Shanghai (104) Nanjing (83) Guangzhou (83) Wuhan (78) Xi'an (75) Hangzhou (71) Chengdu (67) Tianjin (60) Shenzhen (60)
Edge (weight)	Beijing-Tianjin (172) Shenzhen-Suzhou (172) Beijing-Shanghai (171) Beijing-Nanjing (155) Beijing-Wuhan (139) Beijing-Xi'an (127) Lianyungang-Shanghai (120) Beijing-Chengdu (116) Beijing-Dongying (109) Shanghai-Suzhou (106)	Beijing-Tianjin (253) Beijing-Xi'an (191) Beijing-Chengdu (162) Beijing-Nanjing (152) Shenzhen-Suzhou (130) Lianyungang-Shanghai (126) Beijing-Wuhan (119) Beijing-Qingdao (115) Shanghai-Suzhou (115) Beijing-Shanghai (111)

Interregional scale

Interregional network ties are stronger than intraregional network ties

For this research, China was divided into three regions, i.e., the eastern, central and western regions, and interregional urban biomedicine innovation networks were generated between each pair of regions. The basic statistical characteristics of the networks were calculated with the software Gephi to show the spatial structure properties of the Chinese interregional urban biomedicine innovation networks (see Table 3).

From the statistical characteristics of the interregional urban biomedicine innovation networks, it can be seen that the sizes of these networks have evidently grown over time. The numbers of nodes between the eastern and central regions, between the eastern and western regions, and between the central and western regions rose from 17, 12, and 0 in the 2001–2005 period to 196, 176, and 120 in the 2016–2020 period, respectively, and the numbers of edges rose from 13, 11, and 0 in the 2001–2005 period to 733, 522, and 235 in the 2016–2020 period, respectively. In terms of network connectivity, the average degree of the networks rose from 1.53, 1.83, and 0 in the 2001–2005 period to 7.48, 5.93, and 3.92 in the 2016–2020 period, respectively, and the average weighted degree increased from 4.35, 5.50, and 0 in the 2001–2005 period to 69.97, 57.69, and 16.15 in the 2016–2020 period, respectively. As seen from the sizes of the intraregional urban biomedicine innovation networks, the numbers of nodes within the eastern, central and western regions in the 2016–2020 period rose by 1.77 times, 52 times and 104 times, respectively, compared with those in the 2001–2005 period, and the numbers of edges increased by 13.16 times, 271 times and 235 times, respectively.

TABLE 3 Statistical characteristics of interregional urban biomedicine innovation networks among the eastern, central, and western regions of China.

Region	Period	Number of nodes	Number of edges	Average degree	Average weighted degree
Eastern–Eastern	2001–2005	39	63	3.23	12.31
	2006–2010	68	166	4.88	43.15
	2011–2015	97	425	8.76	140.95
	2016–2020	108	892	16.52	355.57
Central–Central	2001–2005	2	1	1.00	1.00
	2006–2010	20	16	1.60	3.30
	2011–2015	70	89	2.54	14.60
	2016–2020	106	272	5.13	33.98
Western–Western	2001–2005	0	0	0.00	0.00
	2006–2010	14	10	1.43	4.43
	2011–2015	55	68	2.47	11.75
	2016–2020	104	235	4.52	24.00
Eastern–Western	2001–2005	12	11	1.83	5.50
	2006–2010	38	49	2.58	14.74
	2011–2015	104	176	3.39	26.31
	2016–2020	176	522	5.93	57.69
Eastern–Central	2001–2005	17	13	1.53	4.35
	2006–2010	59	70	2.37	12.34
	2011–2015	137	271	3.96	36.10
	2016–2020	196	733	7.48	69.97
Central–Western	2001–2005	0	0	0.00	0.00
	2006–2010	4	3	1.50	3.00
	2011–2015	48	51	2.13	8.25
	2016–2020	120	235	3.92	16.15

In terms of network connectivity, the average degrees in the networks rose by 5.08, 4.13 and 4.52 times, respectively, with the average weighted degrees increasing by 27.89, 32.98, and 24 times, respectively. In general, the interregional urban biomedicine innovation networks were superior in both tie closeness and strength to the intraregional urban biomedicine innovation networks, except for the intraregional urban biomedicine innovation network in the eastern region during the 2001–2010 period.

Heterogeneous space with regional central cities as cores formed in the eastern, central, and western regions

As seen from the spatial structure of the urban biomedicine innovation networks on an interregional scale (see Table 4), both the centrality of network nodes and the strength of the intercity biomedicine cooperation in the 2016–2020 period increased greatly compared with those in the 2001–2005 period, with an expansion of the heterogeneous space with regional central cities as cores that formed in the eastern, central and western regions.

It can be seen from the spatial structure in the 2016–2020 period that Beijing was the radiation impetus center of the eastern-central urban biomedicine innovation network, with Wuhan, Shanghai, Nanjing and Zhengzhou serving as subcenters. The main innovation ties in the network occurred between Beijing and cities in the central region, such as Wuhan and Hefei. The spatial structure of the eastern-eastern network is similar to that of the eastern-central network, with Beijing, Shanghai, Nanjing, Guangzhou and Shenzhen serving as important nodes. Many closed subnetworks were formed in the eastern-eastern urban biomedicine innovation network, and these subnetworks were located mainly in Nanjing, Shanghai, Suzhou and other cities in the YRD area and in Foshan, Guangzhou, Shenzhen and other cities in the PRD area.

The eastern-western urban biomedicine innovation network is relatively spatially expansive: in the northern part, four east–west axes are formed from Beijing as an apex to Xi'an, Chengdu, Chongqing and Urumqi in the western region; in the central part, two east–west axes are formed from Shanghai as an apex to Chengdu and Kunming in the western region; in the southern part, one east–west axis is formed between

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TABLE 4 Spatial pattern of the Chinese urban biomedicine innovation network on the interregional scale in the 2016–2020 period.

Region	Nodes (Top 5 in terms of centrality)	Edges (Top 5 in terms of weight. If the weights are more than 100, Top 10 are listed)
Eastern–Eastern (2001–2005)	Beijing (17) Shanghai (14) Guangzhou (10) Tianjin (10) Nanjing (8)	Beijing-Shanghai (19) Beijing-Fushun (16) Beijing-Shenzhen (14) Shenzhen-Nanjing (13) Beijing-Haikou (10)
Eastern–Eastern (2016–2020)	Beijing (94) Shanghai (77) Nanjing (63) Guangzhou (61) Shenzhen (57)	Beijing-Tianjin (784) Beijing-Nanjing (659) Beijing-Shanghai (594) Shenzhen-Suzhou (587) Lianyungang-Shanghai (508) Beijing-Jinan (419) Beijing-Dongying (390) Shanghai-Suzhou (386) Beijing-Shenzhen (383) Beijing-Hangzhou (374)
Eastern–Central (2001–2005)	Beijing (4) Hefei (4) Shanghai (3) Jinan (2) Bengbu (1)	Yuncheng-Shanghai (8) Hefei-Shenzhen (7) Beijing-Hefei (3) Bengbu-Shanghai (2) Beijing-Jingzhou (2)
Eastern–Central (2016–2020)	Beijing (96) Wuhan (54) Shanghai (46) Nanjing (39) Zhengzhou (38)	Beijing-Wuhan (414) Beijing-Hefei (382) Beijing-Zhengzhou (367) Beijing-Changsha (294) Beijing-Changchun (277) Beijing-Puyang (144) Beijing-Daqing (142) Beijing-Nanchang (125) Shenzhen-Wuhan (108) Beijing-Huhhot (105)
Eastern–Western (2001–2005)	Chengdu (4) Shanghai (4) Beijing (3) Kunming (2) Xi'an (2)	Chengdu-Beijing (6) Liuzhou-Shanghai (6) Chongqing-Shanghai (4) Guangzhou-Fangchenggang (3) Xi'an-Beijing (3)
Eastern–Western (2016–2020)	Beijing (59) Xi'an (43) Chengdu (42) Chongqing (32) Nanjing (31)	Beijing-Xi'an (630) Beijing-Chengdu (471) Beijing-Chongqing (402) Beijing-Urumqi (174) Beijing-Yulin (162) Beijing-Kunming (120) Chengdu-Shenzhen (110) Kunming-Shanghai (86) Chengdu-Nanjing (80) Chengdu-Shanghai (77)
Central–Western (2001–2005)	None	None
Central–Western (2016–2020)	Wuhan (32) Xi'an (26) Chongqing (22) Chengdu (21) Changsha (19)	Chengdu-Wuhan (39) Zhengzhou-Chongqing (39) Wuhan-Chongqing (36) Xinxiang-Chongqing (33) Guigang-Wuhan (25)
Western–Western (2001–2005)	None	None
Western–Western (2016–2020)	Chengdu (36) Xi'an (30) Kunming (26) Chongqing (26) Nanning (21)	Chengdu-Mianyang (55) Chengdu-Chongqing (54) Chengdu-Xi'an (43) Xi'an-Xianyang (35) Chengdu-Urumqi (25)
Central–Central (2001–2005)	Yingtan (1) Nanchang (1)	Yingtan-Nanchang (1)
Central–Central (2016–2020)	Wuhan (41) Hefei (32) Changsha (29) Zhengzhou (26) Taiyuan (19)	Ezhou-Wuhan (82) Hefei-Zhengzhou (62) Jingzhou-Wuhan (54) Harbin-Jixin (53) Xinxiang-Zhengzhou (51)

Shenzhen and Chengdu. Biomedical innovation ties are formed among the main nodes, and the distribution of the nodes within the network is relatively unbalanced. The central-western urban biomedicine innovation network exhibits a radial spatial structure with Wuhan as a radiation point that connects with Chengdu, Zhengzhou, and Chongqing. The western-central urban biomedicine innovation network basically spreads toward Wuhan, Xi'an and Chongqing, exhibiting a relatively significant imbalance. The spatial structure of the central-central network is relatively similar to that of the western-western network, with a maximum tie strength of no more than 90. The western-western urban biomedicine innovation network takes Chengdu, Xi'an, Kunming and Chongqing as cores, and the central-central urban biomedicine innovation network takes Wuhan, Hefei, Changsha and Zhengzhou, which are the provincial capitals of Hubei Province, Anhui Province, Hunan Province and Henan Province, respectively, as radiation points.

Urban agglomeration scale

Intraurban-agglomeration network ties are stronger than interurban-agglomeration network ties

With three major Chinese urban agglomerations (BTH, YRD and PRD) being used as spatial units, the urban biomedicine innovation networks of BTH, YRD, PRD, PRD-BTH, PRD-YRD, and YRD-BTH arose separately. The basic statistical characteristics of the networks were calculated with the software Gephi to show the spatial and structural properties of Chinese interurban-agglomeration urban biomedicine innovation networks (see Table 5).

As can be seen from the statistical characteristics of the urban biomedicine innovation networks among the three major Chinese urban agglomerations, the network sizes have increased over time, and all the cities that comprise the urban agglomerations participated in biomedicine innovation

TABLE 5 Statistical characteristics of urban biomedicine innovation networks among BTH, YRD, and PRD.

Period	Urban agglomeration	Number of nodes	Number of edges	Centrality	Weighted centrality
2001–2005	BTH	4	4	2.00	5.50
2006–2010	BTH	8	10	2.50	30.25
2011–2015	BTH	11	19	3.46	119.27
2016–2020	BTH	13	36	5.54	296.15
2001–2005	PRD	5	4	1.60	3.60
2006–2010	PRD	7	7	2.00	10.00
2011–2015	PRD	9	16	3.56	69.11
2016–2020	PRD	9	21	4.67	266.67
2001–2005	YRD	12	14	2.33	7.17
2006–2010	YRD	18	39	4.33	42.67
2011–2015	YRD	25	83	6.64	92.48
2016–2020	YRD	26	141	10.85	263.08
2001–2005	PRD-BTH	4	4	2.00	13.00
2006–2010	PRD-BTH	8	8	2.00	32.25
2011–2015	PRD-BTH	13	13	2.00	66.00
2016–2020	PRD-BTH	16	26	3.25	128.00
2001–2005	PRD-YRD	6	5	1.67	9.33
2006–2010	PRD-YRD	12	11	1.83	10.00
2011–2015	PRD-YRD	22	39	3.55	45.27
2016–2020	PRD-YRD	32	79	4.94	107.44
2001–2005	YRD-BTH	9	9	2.00	9.56
2006–2010	YRD-BTH	18	20	2.22	22.78
2011–2015	YRD-BTH	32	39	2.44	73.31
2016–2020	YRD-BTH	38	80	4.21	176.21

cooperation during the mature phase. Both the network connectivity and the network ties strength of an intraurban-agglomeration network are stronger than those of an interurban-agglomeration network. In terms of network connectivity, the intraurban-agglomeration network of the YRD has the strongest connectivity among the three major urban agglomerations. The interurban-agglomeration network between the PRD and YRD urban agglomerations has the strongest connectivity of the interurban-agglomeration networks. In terms of network tie strength, the intraurban-agglomeration network of BTH is the strongest among the three major urban agglomerations. The interurban agglomeration network between the YRD and BTH urban agglomerations has the strongest ties in the interurban agglomeration networks.

Radial spatial structure with central cities as hubs formed in three major urban agglomerations

As seen from the spatial structure of the urban biomedicine innovation networks on the urban agglomeration scale, both the centrality of network nodes and the intercity urban biomedicine cooperation strength were greatly increased in the 2016–2020 period compared with those in the 2001–2005 period, while the radial network structure using the central cities of the urban agglomerations as cores was enhanced.

The biomedical innovation networks of BTH, the YRD and the PRD have developed over the 2001–2005 period from single-core urban agglomerations with Beijing, Shanghai and Guangzhou serving as those single cores, respectively, to double-core urban agglomerations using Beijing and Shijiazhuang, Nanjing and Shanghai, and Guangzhou and Shenzhen as double cores, respectively (see Table 6). In the biomedical innovation network within the PRD urban agglomeration, cooperation was mainly carried out by Guangzhou with other cities, including Shenzhen and Foshan. In the biomedical innovation network within the YRD urban agglomeration, cooperation was mainly carried out by Nanjing and Shanghai with other cities, including Suzhou and Hangzhou. In the network within the BTH urban agglomeration, cooperation was mainly carried out by Beijing with other cities, including Shijiazhuang and Tianjin.

In the interurban-agglomeration biomedicine innovation cooperation, the PRD-YRD had a double core structure with Guangzhou and Shenzhen as the cores, and both the PRD-BTH and the YRD-BTH used a single-core structure with Beijing as the single core. In the interurban-agglomeration biomedicine

TABLE 6 Spatial pattern of Chinese urban biomedicine innovation networks on the interregional scale in the 2016–2020 period.

Region	Nodes (Top 5 in terms of centrality)	Edges (Top 5 in terms of weight. If the weights are more than 100, then the Top 10 are listed)
2001–2005 The PRD	Guangzhou (4) Foshan (1) Dongguan (1) Jiangmen (1) Shenzhen (1)	Guangzhou-Shenzhen (4) Fosha-Guangzhou (2) Guangzhou-Jiangmen (2) Guangzhou-Dongguan (1)
2016–2020 The PRD	Guangzhou (8) Shenzhen (8) Dongguan (6) Foshan (5) Zhuhai (4)	Guangzhou-Shenzhen (295) Foshan-Guangzhou (203) Guangzhou-Zhaoqing (202) Dongguang-Guangzhou (113) Guangzhou-Zhuhai (112)
2001–2005 The YRD	Shanghai (7) Hangzhou (4) Nanjing (4) Shaoxing (3) Jinhua (2)	Shanghai-Suzhou (7) Shanghai-Shaoxing (6) Hangzhou-Jinhua (5) Nanjing-Jiaxing (4) Taizhou-Shanghai (4)
2016–2020 The YRD	Nanjing (23) Shanghai (21) Hefei (20) Hangzhou (19) Suzhou (18)	Shanghai-Suzhou (386) Nanjing-Shanghai (196) Hangzhou-Shanghai (148) Nanjing-Suzhou (142) Shanghai-Taizhou (131) Shanghai-Shaoxing (111) Nantong-Shanghai (107)
2001–2005 The BTH	Beijing (3) Shijiazhuang (2) Tianjin (2) Langfang (1)	Beijing-Shijiazhuang (4) Beijing-Tianjin (4) Beijing-Langfang (2) Tianjin-Shijiazhuang (1)
2016–2020 The BTH	Beijing (12) Shijiazhuang (12) Tianjin (9) Baoding (7) Tangshan (5)	Beijing-Tianjin (784) Beijing-Shijiazhuang (328) Beijing-Langfang (275) Baoding-Beijing (148) Baoding-Shijiazhuang (59)
2001–2005 The PRD-The YRD	Hefei (2) Guangzhou (2) Shenzhen (2) Nanjing (2) Shanghai (1)	Shenzhen-Nanjing (13) Hefei-Shenzhen (7) Shanghai-Guangzhou (5) Zhaoqing-Nanjing (2) Hefei-Guangzhou (1)
2016–2020 The PRD-The YRD	Guangzhou (19) Shenzhen (17) Zhuhai (10) Shanghai (8) Zhongshan (8)	Shenzhen-Suzhou (587) Guangzhou-Shanghai (154) Shanghai-Shenzhen (99) Nanjing-Shenzhen (68) Guangzhou-Nanjing (63)
2001–2005 The PRD-The BTH	Beijing (2) Guangzhou (2) Shenzhen (2) Tianjin (2)	Beijing-Shenzhen (14) Guangzhou-Tianjin (7) Beijing-Guangzhou (3) Tianjin-Shenzhen (2)
2016–2020 The PRD-The BTH	Beijing (9) Shenzhen (6) Guangzhou (6) Tianjin (5) Zhuhai (4)	Beijing-Shenzhen (383) Beijing-Guangzhou (278) Guangzhou-Tianjin (59) Beijing-Dongguan (56) Beijing-Zhuhai (42)
2001–2005 The YRD-The BTH	Beijing (5) Shanghai (3) Tianjin (3) Suzhou (2) Hangzhou (1)	Beijing-Shanghai (19) Beijing-Hangzhou (4) Beijing-Wuxi (4) Suzhou-Tianjin (4) Xingtai-Shanghai (4)
2016–2020 The YRD-The BTH	Beijing (26) Tianjin (16) Shanghai (11) Nanjing (9) Shijiazhuang (8)	Beijing-Nanjing (659) Beijing-Shanghai (594) Beijing-Hefei (382) Beijing-Hangzhou (374) Beijing-Suzhou (185) Beijing-Jinhua (132)

innovation cooperation network between the PRD and the YRD urban agglomerations, the level of cooperation between Guangzhou and Shenzhen in the PRD and between Shanghai and Suzhou in the YRD was dominant. In the interurban-agglomeration biomedicine innovation cooperation network between the PRD and BTH, the level of cooperation between Beijing in the BTH and Guangzhou and Shenzhen in the PRD was dominant. In the interurban-agglomeration biomedicine innovation cooperation network between the YRD and the BTH, the cooperation between Beijing in the BTH and Nanjing and Shanghai in the YRD was dominated.

Provincial scale

Intraprovincial biomedical innovation networks have poor connectivity and low internal tie strength

The intraprovincial urban biomedicine innovation networks in 27 provinces, including Shaanxi, Shandong, and Guangdong, over the 2016–2020 period were investigated from the perspective of provincial scale (see Table 7). The network size of the urban biomedical innovation network in each province is small. In terms of network connectivity, the average degrees differ greatly among the provinces: the average degrees of eight provinces, i.e., Jiangsu, Shandong, Guangdong, Zhejiang, Fujian, Sichuan, Anhui, and Henan, are 3.05 higher than the average value, indicating a relatively high level of connectivity among the node cities within the network. The average degrees of Heilongjiang, Hainan, Ningxia and Tibet are lower than 2.0, while those of the other provinces are within the range of 2.0–3.0. In general, the connectivity among cities in the networks is not strong, with insufficient local networking. In the entire country, the average intraprovincial ties strength made up less than one tenth of the average strength of the total ties, which means that compared with interprovincial ties, the intraprovincial ties were relatively weak.

The intraprovincial biomedicine innovation network forms a core-periphery structure with a provincial capital as the core

Table 8 shows that the provinces with multicore urban biomedical innovation networks include Shandong (with Jinan,

TABLE 7 Statistical characteristics of the intraprovincial urban biomedicine innovation networks of All Chinese Provinces in the 2016–2020 period.

Province	Number of nodes	Number of edges	Average degree	Average weighted degree	Proportion of intraprovincial ties (%)	Province	Number of nodes	Number of edges	Average degree	Average weighted degree	Proportion of intraprovincial ties (%)
Anhui	16	30	3.75	23.13	0.119	Jiangxi	6	6	2.00	30.00	0.052
Fujian	9	17	3.78	54.22	0.092	Liaoning	10	11	2.20	8.00	0.062
Gansu	9	10	2.22	10.67	0.112	Inner Mongolia	10	11	2.20	6.40	0.093
Guangdong	21	61	5.81	174.95	0.114	Ningxia	3	2	1.33	5.33	0.043
Guangxi	13	16	2.46	13.69	0.119	Qinghai	4	4	2.00	4.50	0.100
Guizhou	7	8	2.29	11.43	0.099	Shandong	17	54	6.35	96.35	0.117
Hainan	6	5	1.67	4.67	0.086	Shanxi	10	14	2.80	14.60	0.113
Hebei	11	16	2.91	26.73	0.077	Shanxi	9	10	2.22	17.78	0.060
Henan	17	29	3.41	33.06	0.104	Sichuan	17	32	3.77	25.29	0.116
Heilongjiang	9	8	1.78	16.44	0.079	Tibet	2	1	1.00	1.00	0.025
Hubei	15	19	2.53	39.73	0.082	Xinjiang	13	15	2.31	8.46	0.133
Hunan	12	16	2.67	21.17	0.088	Yunnan	16	24	3.00	15.25	0.156
Jilin	7	9	2.57	14.29	0.087	Zhejiang	11	29	5.27	103.09	0.088
Jiangsu	13	53	8.15	183.54	0.089						

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Qingdao, and Yantai as the main nodes), Zhejiang (with Hangzhou, Ningbo and Shaoxing as the main nodes), Jiangsu (with Nanjing, Suzhou, Wuxi, and Yangzhou as the main nodes), and Fujian (with Fuzhou, Xiamen, and Quanzhou as the main nodes). Guangdong (with Guangzhou and Shenzhen as the main nodes) has a double-core network. Qinghai and Tibet only form biomedicine innovation ties between Haidong-Xining and Lhasa-Linzhi, respectively. Most of the other provinces use a core-periphery structure with the provincial capital as the core. The provinces with intraprovincial tie strengths of >90 include Guangdong, Jiangsu and Shandong, which means that the intraprovincial tie strengths in these provinces are relatively high. The provinces with intraprovincial tie strengths of <10 include Gansu, Hainan, Liaoning, Inner Mongolia, Ningxia, Qinghai, and Tibet, indicating that the intraprovincial tie strengths in these provinces are relatively low.

Conclusions and discussions

Conclusions

This paper analyzes the spatiotemporal evolution of the Chinese urban biomedicine innovation network pattern on four scales, i.e., the national scale, interregional scale, urban agglomeration scale, and provincial scale, using Chinese biomedicine patent cooperation data from the incoPat GPD (2001–2020) and the SNA method to investigate the structure of Chinese urban biomedicine innovation networks. The following conclusions were drawn:

(1) The evolution process of the Chinese national biomedicine innovation network was divided into four phases, namely, the starting phase, growing phase, expanding phase, and mature phase. In all four phases, the network took Beijing and Shanghai as the cores, with its density and complexity continuously improving over time, and its density increased from west to east. Generally, the overall ties in the Chinese national urban biomedicine innovation network have been gradually strengthening, the cooperation scope has been somewhat expanding, and the polarization effect of the network has gradually disappeared. The COVID-19 pandemic has not had an impact on Chinese biomedicine innovation cooperation. In contrast, the numbers of nodes and edges and the centrality and weighted centrality of the network all increased.

(2) On the interregional scale, the interregional urban biomedical innovation networks were superior in both tie closeness and strength to the intraregional urban innovation networks, except for the intraregional urban biomedical innovation network in the eastern region over the 2001–2010 period. Both the centrality of network nodes and the level of intercity biomedicine cooperation in the 2016–2020 period were greatly enhanced compared with those in the 2001–2005 period, with an expansion of the heterogeneous space using regional central cities as cores that formed in the eastern, central and western regions.

(3) The sizes of the urban biomedicine innovation networks among the three major urban agglomerations have evidently increased, and all the cities in the urban agglomerations participated in biomedicine innovation cooperation during the mature phase. The BTH, YRD, and PRD urban agglomerations all developed from single-core urban agglomerations into double-core urban agglomerations. In the interurban-agglomeration biomedicine innovation cooperation, the PRD and the YRD form a double-core urban agglomeration with Guangzhou and Shenzhen as the double cores, while the PRD to BTH and the YRD to BTH networks form single-core urban agglomerations that use Beijing as the core.

(4) On the provincial scale, all intraprovincial biomedicine innovation networks have relatively small sizes, with large variations in average degree, weak connectivity and low internal ties. Each intraprovincial biomedicine innovation network has formed a core-periphery structure with the provincial capital as the center. Excepting Guangdong, Jiangsu and Shandong, the internal ties strengths in all other provinces are lower than 90.

Improvement and suggestions

(1) It is necessary to fully consider the radiation effects and impetus functions of such central cities as Beijing, Shanghai, Guangzhou, and Shenzhen, and to actively upgrade the function of the edge cities in the entire network through cooperation with the surrounding cities so that they better accept new innovation relationships. A coordinative biomedicine innovation mechanism should be set up to break the communication entanglements and political barriers between cities, promote the integration of intercity biomedicine innovation elements and impair polarization within the network.

(2) Geographical distance plays an important role in the urban biomedicine innovation network. The further the distance between two cities is, the weaker their ties will be. As a result, it is necessary to strengthen the construction of the transportation network in China to lessen the costs of innovation ties between cities.

(3) A government is both an important leader in urban innovation and a formulator of policies, playing a key role in urban biomedicine innovation cooperation. The government should accelerate the implementation of incentive policies regarding biomedicine innovation cooperation and strengthen the protection of property rights within biomedicine. In addition, the government

TABLE 8 Statistical characteristics of the intra-provincial urban biomedicine innovation networks of all Chinese provinces in the 2016–2020 period.

Province	Nodes (Centrality)	Edges (Weight)
Anhui	Hefei (15) Huaibei (6) Huainan (5) Fuyang (4) Chuzhou (4)	Hefei-Tongling (28) Hefei-Huaibei (25) Hefei-Huainan (16) Fuyang-Hefei (15) Chuzhou-Hefei (10)
Fujian	Fuzhou (8) Xiamen (6) Zhangzhou (5) Quanzhou (4) Longyan (3)	Fuzhou-Xiamen (40) Fuzhou-Sanming (34) Xiamen-Zhangzhou (31) Quanzhou-Xiamen (28) Fuzhou-Ningde (24)
Gansu	Lanzhou (8) Baiyin (3) Dingxi (2) Zhangye (2) Jinchang (1)	Baiyin-Lanzhou (9) Jiuquan-Lanzhou (9) Dingxi-Lanzhou (6) Lanzhou-Zhangye (6) Jinchang-Lanzhou (5)
Guangdong	Guangzhou (20) Shenzhen (18) Dongguan (10) Foshan (10) Zhanjiang (6)	Guangzhou-Shenzhen (295) Foshan-Guangzhou (203) Guangzhou-Zhaoqing (202) Dongguan-Guangzhou (113) Guangzhou-Zhuhai (112)
Guangxi	Nanjing (12) Laibin (3) Guilin (3) Baise (2) Hezhou (2)	Laibin-Nanning (11) Beihai-Nanning (10) Nanning-Baise (10) Nanning-Guilin (9) Nanning-Qinzhou (9)
Guizhou	Guiyang (6) Qiannanzhou (3) Anshun (2) Bijie (2) Tongren (1)	Guiyang-Qianxinanzhou (10) Bijie-Guiyang (8) Guiyang-Zunyi (7) Anshun-Guiyang (6) Bijie-Anshun (2)
Hainan	Haikou (5) Chengmai (1) Danzhou (1) Ding'an (1) Sanya (1)	Haikou-Sanya (6) Chengmai-Haikou (3) Danzhou-Haikou (2) Ding'an-Haikou (2) Lingshui-Haikou (1)
Hebei	Shijiazhuang (10) Baoding (5) Tangshan (3) Cangzhou (2) Hengshui (2)	Baoding-Shijiazhuang (59) Langfang-Shijiazhuang (37) Cangzhou-Shijiazhuang (9) Shijiazhuang-Qinhuangdao (9) Shijiazhuang-Tangshan (6)
Henan	Zhengzhou (15) Xinxiang (5) Xuchang (5) Pingdingshan (4) Anyang (3)	Xinxiang-Zhengzhou (51) Sanmenxia-Zhengzhou (41) Luoyang-Zhengzhou (39) Anyang-Zhengzhou (21) Nanyang-Zhengzhou (20)
Heilongjiang	Harbin (8) Daqing (1) Jixi (1) Jiamusi (1) Mudanjiang (1)	Harbin-Jixi (53) Suihua-Harbin (9) Daqing-Harbin (4) Harbin-Mudanjiang (3) Harbin-Qiqiha'er (2)
Hubei	Wuhan (14) Enshi (3) Yichang (3) Jingmen (2) Jingzhou (2)	Ezhou-Wuhan (82) Jingzhou-Wuhan (54) Huanggang-Wuhan (32) Wuhan-Xiaogan (22) Jingmen-Wuhan (19)
Hunan	Changsha (11) Xiangtan (4) Changde (3) Zhuzhou (3) Xiangxi (3)	Changde-Zhuzhou (38) Huaihua-Changsha (25) Xiangtan-Changsha (16) Changde-Changsha (9) Yueyang-Changsha (8)
Jilin	Changchun (6) Yanbian (4) Tonghua (3) Jilin (2) Siping (1)	Jilin-Tonghua (10) Jilin-Changchun (9) Yanbian-Changchun (8) Changchun-Tonghua (7) Siping-Changchun (6)
Jiangsu	Nanjing (12) Suzhou (12) Wuxi (11) Yangzhou (11) Zhenjiang (9)	Nanjing-Suzhou (142) Nanjing-Taizhou (95) Lianyungang-Nanjing (91) Nanjing-Wuxi (87) Changzhou-Nanjing (74)
Jiangxi	Nanchang (5) Ganzhou (2) Shangrao (2) Ji'an (1) Jiujiang (1)	Nanchang-Yichun (48) Nanchang-Jiujiang (19) Ganzhou-Nanchang (8) Ji'an-Nanchang (6) Ganzhou-Shangrao (5)
Liaoning	Shenyang (8) Dalian (4) Benxi (2) Jinzhou (2) Anshan (1)	Dalian-Shenyang (8) Dalian-Jinzhou (6) Shenyang-Tieling (5) Fushun-Shenyang (4) Liaoyang-Shenyang (4)
Inner Mongolia	Huhhot (9) Hinggan League (3) Chifeng (2) Tongliao (2) Bayannur (1)	Huhhot-Hinggan League (8) Huhhot-Xilingol League (5) Hinggan League-Hinggan League (4) Huhhot-Chifeng (3) Huhhot-Ulanqab (3)
Ningxia	Yinchuan (2) Wuzhong (1) Guyuan (1)	Wuzhong-Yinchuan (7) Yinchuan-Guyuan (1)
Qinghai	Haixi (1) Xining (1)	Haidong-Xining (6)
Shandong	Jinan (15) Qingdao (12) Yantai (10) Tai'an (8) Zibo (8)	Qingdao-Weifang (116) Jinan-Qingdao (71) Dezhou-Jinan (52) Jinan-Taian (51) Jinan-Jining (40)
Shanxi	Taiyuan (9) Jinzhong (5) Linfen (3) Lvliang (3) Jincheng (2)	Jinzhong-Taiyuan (34) Taiyuan-Xinzhou (7) Taiyuan-Changzhi (7) Taiyuan-Yuncheng (5) Linfen-Taiyuan (3)
Shaanxi	Xi'an (8) Weinan (3) Ankang (2) Xianyang (2) Baoji (1)	Xi'an-Xianyang (35) Xi'an-Yulin (11) Baoji-Xi'an (9) Hanzhong-Xi'an (9) Xi'an-Ankang (7)
Sichuan	Chengdu (16) Liangshan (7) Yibin (7) Luzhou (6) Panzhihua (6)	Chengdu-Mianyang (55) Chengdu-Panzhihua (21) Chengdu-Meishan (15) Chengdu-Zigong (14) Chengdu-Leshan (13)
Tibet	Lhasa (1) Linzhi (1)	Lhasa-Linzhi (1)

(Continued)

TABLE 8 (Continued)

Province	Nodes (Centrality)	Edges (Weight)
Xinjiang	Ili (4) Changji (3) Bayingolin (2) Shihezi (2) Aksu	Urumqi-Ili Kazak Autonomous Prefecture (13) Changji Hui Autonomous Prefecture-Urumqi (10) Turpan-Urumqi (6) Bayingolin Mongol Autonomous Prefecture-Urumqi (4) Shihezi-Ili Kazak Autonomous Prefecture (3)
Yunnan	Kunming (15) Chuxiong (5) Xishuangbanna (4) Honghe (4) Dehong Prefecture (3)	Kunming-Yuxi (19) Xishuangbanna Dai Autonomous Prefecture-Kunming (17) Kunming-Lincang (9) Baoshan-Kunming (7) Chuxiong Yi Autonomous Prefecture-Kunming (6)
Zhejiang	Hangzhou (10) Ningbo (8) Shaoxing (7) Huzhou (5) Jiaxing (5)	Hangzhou-Shaoxing (99) Hangzhou-Taizhou (88) Hangzhou-Ningbo (81) Hangzhou-Huzhou (51) Hangzhou-Jinhua (51)

should establish an innovation foundation to increase investment in biomedical innovation.

Theoretical contribution

(1) This research deals with Chinese urban biomedicine innovation networks on multiple scales, i.e., the national scale, urban agglomeration scale, interregional scale, and provincial scale, by using a three-dimensional method based on the original innovation network research approaches to reveal the pattern characteristics of the innovation networks across different scales. It breaks the limitation of using a single scale on innovation networks and enriches the theoretical system of innovation geography.

(2) Research on urban innovation networks is an important component of research on innovation systems. This research evaluates Chinese urban biomedicine innovation capability on the basis of data related to urban biomedicine patent cooperation, and it contributes to the filed not only by deepening the research on innovation system theory but also by the application of this theory.

(3) This research thoroughly analyzes the positions and functions of various node cities in the innovation networks on the urban agglomeration scale, interregional scale, and provincial scale, etc., and it is conducive not only to enhancing the understanding of the innovative development functions of cities but also to deepening the research on urban geographical theory.

Shortcomings of research and prospects

(1) This paper studies Chinese urban biomedicine innovation networks solely on the basis of patent cooperation data, which appears to be slightly one-sided for fully describing Chinese biomedicine innovation networks. Next, on the basis of data availability, future research can be conducted with the data related to cooperative papers to comprehensively describe the level of Chinese biomedicine innovation.

(2) Owing to its length, this paper does not analyze the factors influencing Chinese biomedical innovation networks. In future research efforts, the evolution mechanism of the networks can be further explored on the basis of this research.

(3) Considering the research and development of patents requires a certain amount of time, the data set needs to be further expanded in the future. The conclusion made on the basis of an investigation into Chinese biomedicine innovation networks during the 2019–2020 period that found the COVID-19 pandemic has not had a negative impact upon the network needs further testing.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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