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## EDITED BY

Antonino Morabito,  
University of Florence, Italy

## REVIEWED BY

Mohsen Norouzinia,  
Shahid Beheshti University of Medical  
Sciences, Iran  
Sicheng Zhang,  
Anhui Provincial Children's Hospital, China

## \*CORRESPONDENCE

Xiaohui Wang  
✉ 7655100@qq.com

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# The digital transformation and future era: bibliometric view of artificial intelligence application in pediatric surgery

Boshen Shu, Shufeng Zhang, Jian Gao, Lin Wang and  
Xiaohui Wang\*

Department of Pediatric Surgery, Henan Provincial People's Hospital, Zhengzhou, Henan, China

**Introduction:** Artificial intelligence has been extensively used in the personalized diagnosis and treatment of pediatric surgery. Numerous articles have been published related to this research recently. Consequently, we aimed to perform a bibliometric analysis of influential studies to reveal the digital transformation and future era within pediatric surgery.

**Methods:** We searched publications on artificial intelligence application in pediatric surgery until December 31, 2023, via Web of Science core collection database comprehensively. Of these, the 100 most cited articles were evaluated in detail. Diverse parameters including total citations, publication year, journal, impact factor, impact index, country, organization, keyword, study design and evidence level were analyzed. Bibliometrix package from Rstudio, VOSviewer and GraphPad Prism were used for data analysis and mapping.

**Results:** A total of 2,799 publications were searched and the 100 most cited articles were published from 1995 to 2023, with a total citation number of 2,770. The top country and organization contributing to this area were the USA and Stanford University, while the *Journal of Pediatric Surgery* dominated the number of studies from the top 100. Retrospective study and articles with evidence level III were the most common. For keyword co-occurrence analysis, it indicated necrotizing enterocolitis, congenital heart disease and radiomics dominated potential hotspots in the future.

**Conclusions:** The present study presents a detailed list of the impactful articles on artificial intelligence application in pediatric surgery. It provides insights into potential cooperation and prospects for future research, which plays a helpful reference for researchers studying on artificial intelligence application in pediatric surgery.

## KEYWORDS

artificial intelligence, AI, pediatric surgery, bibliometrics, visualized study

## 1 Introduction

Artificial intelligence (AI) mainly refers to the utilization of computers or machines to simulate human intelligent behavior, including learning, cognitive functions, problem-solving, perception and many other characteristics (1). Since McCarthy et al. mentioned the AI conception in the 1950s, it has progressively evolved to be a multidisciplinary subject (2). Incorporating various areas such as computing, mathematics, biology, mechanical engineering and several more sectors. Due to the powerful potential of its

advanced algorithms and learning capabilities, AI has demonstrated significant application in different medical domains like cardiovascular disease and rheumatic disease (3, 4). It now shows considerable reliability in disease diagnosis, prognosis prediction, drug research, as well as other fields (5, 6).

Wide applications of AI hold substantial potential to transform child and adolescent health digitally. The special challenges related to children, containing distinctive developmental and physiological requirements, heterogeneous cognitive capabilities, and natural communication problems, emphasize the revolutionary potential of AI in this area (7). For pediatric surgery, precise diagnosis, timely predictions, patient's safety and therapy strategies can be remarkably reinforced by the combination with AI in patient care process (8). Notably, numerous articles were published related to AI application in pediatric surgery recently. Consequently, it is of crucial importance for scholars to grasp the latest studies for reviewing the substantial update. Bibliometric analysis is a type of statistical approach that takes citation counts as a main measure of research influence, serving as a useful tool to evaluate development tendencies of a certain research field (9). This method has been applied in many different medical research fields to depict the knowledge structure and development trends till today (10, 11). However, to the best of our knowledge, there is no research on bibliometric analysis for artificial intelligence application in pediatric surgery. Hence, we aimed to perform a bibliometric analysis to explore the current research topics and cooperative networks in the application of AI in pediatric surgery over recent years, for the purpose of providing a theoretical reference for scholars to better seize the research frontiers and future trends.

## 2 Materials and methods

### 2.1 Data collection and search strategy

In October 2024, we performed a literature search in Web of Science Core Collection (WoSCC). A comprehensive review of pertinent studies was taken to support the formulation for our search strategy. Besides, for obtaining only related search results, a "title" instead of "topic" searching strategy was used (12, 13). Concerning the application of AI in pediatric surgery, we conducted the following searching terms: ("artificial intelligence" OR "computational intelligence" OR "machine learning" OR "deep learning" OR "decision trees" OR "decision forest" OR "expert system" OR "fuzzy logic" OR "automatic programming" OR "autonomous robot" OR "intelligent agent" OR "neural net" OR "voice recognition" OR "text mining" OR "electronic health record" OR "AI" OR "ML" OR "SVM" OR "Random forest" OR "Logistic regression" OR "RNN" OR "LSTM") (Title) AND ("neonate" OR "neonates" OR "neonatal" OR "infant" OR

"infants" OR "infancy" OR "preterm" OR "preterms" OR "newborn" OR "newborns" OR "pediatric" OR "pediatrics" OR "children" OR "child" OR "boy" OR "girl" OR "boys" OR "girls" OR "adolescent" OR "congenital" OR "atresia" OR "tracheoesophageal fistula" OR "necrotizing enterocolitis" OR "Hirschsprung disease" OR "anorectal malformation" OR "neuroblastoma" OR "hepatoblastoma" OR "nephroblastoma" OR "wilms" OR "orchidopexy" OR "pyloromyotomy" OR "Kasai" OR "imperforate anus" OR "pediatric surgery") (Title) AND LA = (English) AND Publication time span = (1 January 1945 to 31 December 2023).

### 2.2 Data extraction and including criteria

The included articles were restricted to those that (1) involved AI applications, (2) and were relevant to pediatric surgery field (3) were published as article or review. Two independent authors screened all the publications by reading abstracts or full text according to the criteria. Differences between these two authors were resolved through thorough discussion. The selected articles based on the unanimous decision from these two reviewers were ranked in a descending order and the first 100 came to be the final list.

The following factors of the 100 most cited manuscripts were recorded and analyzed: total citations, publication year, journal, impact factor (IF), impact index, country, organization, keyword, study design and evidence level. The impact index is calculated by dividing the duration time (unit: year) since publication by the number of cited times, multiplied by 100, with lower outcome demonstrating a more robust impact (14). The study designs included retrospective study, prospective study, review, case-control study, randomized controlled trial (RCT), meta-analysis and systematic review. The evidence levels were arranged in accordance with Cashin et al. from high to low: meta-analysis (Level I), RCT (Level I), systematic review (Level I), prospective study (Level II), retrospective study (Level III), review (Level IV) and case-control study (Level IV) (15). Level I and II were defined as high evidence levels.

### 2.3 Data analysis and visualization

Statistical analyses were conducted with GraphPad Prism v. 7.0 (GraphPad, La Jolla, CA, USA). All tests were two-sided. Spearman correlation coefficient was applied to examine correlations among selected continuous variables. Unpaired *t* tests were taken to make the comparison between two different groups for parametric data and the One-way ANOVA test was performed for non-parametric data. The *P* Value of <0.05 was considered statistically significant.

Visualized analysis for country and organization collaboration, as well as keyword co-occurrence network analysis were conducted by VOSviewer 1.6.20 (Leiden University, Leiden, The Netherlands). Here, the line thickness between the colored nodes represents the total link strength. While for bibliometrix package from Rstudio,

#### Abbreviations

AI, artificial intelligence; CHD, congenital heart disease; DL, deep learning; IF, impact factor; ML, machine learning; RCT, randomized controlled trial; WoSCC, web of science core collection.

the “Most Relevant Sources” function was applied to describe the rank of publications from different journals. The “Most Relevant Affiliations” function was used to identify the contribution from different organizations.

## 3 Results

### 3.1 Overview

A total of 2,799 manuscripts were identified by the initial search. The top 100 cited articles were published between 1995 and 2023 and they were presented accordingly in [Table 1](#). The total number of citations was 2,773 (2,710 without self-citations; range from 11 to 162). The number of publications and citations each year generally increased from 1995 to 2023 and the year 2021 held the leading position in the number of publications ( $n = 35$ ) ([Figure 1A](#)). The most cited article entitled “Prediction of progression of the curve in girls who have adolescent idiopathic scoliosis of moderate severity. Logistic regression analysis based on data from The Brace Study of the Scoliosis Research Society” was published in 1995 by Peterson et al. in *Journal of Bone and Joint Surgery-American Volume* (16). While the article with the lowest impact index entitled “Real-time cardiovascular MR with spatio-temporal artifact suppression using deep learning-proof of concept in congenital heart disease” was published in 2019 by Hauptmann A et al. in the journal *Magnetic Resonance in Medicine* (17). There were 75 retrospective studies, 9 prospective studies, 9 reviews, 3 case-control studies, 2 RCTs, 1 meta-analysis and 1 systematic review papers on the top 100 list. Articles with evidence level III dominated the leading position ( $n = 75$ ), followed by level IV ( $n = 12$ ) and level II ( $n = 9$ ) ([Figure 1B](#)). There was no significant difference between evidence level with either citation number per article ( $P = 0.057$ ) ([Figure 1C](#)) or impact factor of the corresponding journal ( $P = 0.095$ ) ([Figure 1D](#)). The number of cited times did not correlate with the IF ( $r = 0.161$ ,  $P = 0.112$ ) ([Figure 2A](#)) or II ( $r = -0.178$ ,  $P = 0.077$ ) ([Figure 2B](#)) per article significantly.

### 3.2 Analysis of countries and organizations

For the comprehensive and detailed analysis of contributing countries and organizations to these top 100 cited publications, we took the “individual authorship strategy” for counting countries or organizations. Briefly, if two authors from one paper came from the same country or organization, we counted the number of contributions about this country or organization as two rather than one.

A total of 41 countries have contributed related articles in the list. Of these, the USA dominated the global publication pattern ( $n = 52$ ) ([Figure 3A](#)) as well as the leading position in country-wise collaboration, with the most total link strength ( $n = 2,552$ ) ([Figure 3B](#)). It is pivotal to emphasize the broad country-wise

collaboration in scientific work. Notable partnerships involved close collaborations among the USA, China and Germany ([Figure 3B](#)). Notwithstanding these active cooperations, there was a noticeable imbalance in different countries regarding research collaboration.

There were 304 organizations contributing to the 100 most cited manuscripts. The Stanford University dominated the publication number position ( $n = 23$ ) ([Figure 3C](#)). While for the organization level collaboration, Children’s Hospital of Philadelphia had the highest total link strength ( $n = 567$ ) ([Figure 3D](#)).

### 3.3 Analysis of authors and journals

Similar to the “individual authorship strategy” for counting countries or organizations we applied in the analysis of countries and organizations. Here, for example, if one author played as both first and corresponding author, we counted this author’s authorship as two rather than one.

Bertsimas D. from Massachusetts Institute of Technology held the leading position for the number of publications ( $n = 3$ ) in the top 100 cited list. While for the international collaboration network analysis for authors, Arafati A. from University of California owned the highest total link strength ( $n = 498$ ) ([Figure 4A](#)). However, from the collaboration analysis, we can find collaborations from authors in different organizations and countries were still not enough and should be enhanced.

There were 77 journals contributing to the top 100 cited papers. Of these, the *Journal of Pediatric Surgery* dominated the number of studies ( $n = 5$ ; IF = 2.4), followed by the *Frontiers in Cardiovascular Medicine* ( $n = 4$ ; IF = 2.8) and *PLOS ONE* ( $n = 4$ ; IF = 2.9) ([Figure 4B](#)).

### 3.4 Keyword co-occurrence analysis

From keyword network visualization ([Figure 4C](#)) and overlay visualization ([Figure 4D](#)) based on VOSviewer, we might identify the current hotspots and future trends of artificial intelligence application in pediatric surgery, for a better understanding of the development of research key points. Our study contained a total of 560 all keywords, and there were 106 keywords with a frequency of more than or equal 2 times. The size of the colored nodes stands for the frequency of keyword occurrence, indicating the focus within the area. The linking lines between nodes represent the strength of connection, with thicker lines demonstrating more often co-appearance in one article. This network visualization promoted the recognition of eminent topics and associations in all keywords. [Figure 4C](#) depicted notable high-frequency keywords, including machine learning (ML), AI, DL, children, CHD and so on. When focusing on the emerging research cores in this field, we found necrotizing enterocolitis, CHD and radiomics may dominate potential hotspots in the future ([Figure 4D](#)).

TABLE 1 The top 100 cited articles on AI application in pediatric surgery.

| Rank | Author           | Title                                                                                                                                                                                                            | Journal                                           | Citations (N) | Year | Impact factor | Impact index |
|------|------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------|---------------|------|---------------|--------------|
| 1    | Peterson et al.  | Prediction of progression of the curve in girls who have adolescent idiopathic scoliosis of moderate severity. Logistic regression analysis based on data from The Brace Study of the Scoliosis Research Society | JOURNAL OF BONE AND JOINT SURGERY-AMERICAN VOLUME | 162           | 1995 | 4.4           | 17.9         |
| 2    | Hauptmann et al. | Real-time cardiovascular MR with spatio-temporal artifact suppression using deep learning-proof of concept in congenital heart disease                                                                           | MAGNETIC RESONANCE IN MEDICINE                    | 134           | 2019 | 3             | 3.7          |
| 3    | Zhang et al.     | Deep Learning-Based Multi-Omics Data Integration Reveals Two Prognostic Subtypes in High-Risk Neuroblastoma                                                                                                      | FRONTIERS IN GENETICS                             | 102           | 2018 | 2.8           | 5.9          |
| 4    | Ladefoged et al. | Deep Learning Based Attenuation Correction of PET/MRI in Pediatric Brain Tumor Patients: Evaluation in a Clinical Setting                                                                                        | FRONTIERS IN NEUROSCIENCE                         | 79            | 2019 | 3.2           | 6.3          |
| 5    | Hale et al.      | Machine-learning analysis outperforms conventional statistical models and CT classification systems in predicting 6-month outcomes in pediatric patients sustaining traumatic brain injury                       | NEUROSURGICAL FOCUS                               | 67            | 2018 | 3.3           | 9.0          |
| 6    | Neff et al.      | Prediction of mortality and need for neonatal extracorporeal membrane oxygenation in fetuses with congenital diaphragmatic hernia: Logistic regression analysis based on MRI fetal lung volume measurements      | AMERICAN JOURNAL OF ROENTGENOLOGY                 | 65            | 2007 | 4.7           | 26.2         |
| 7    | Büsing et al.    | MR lung volume in fetal congenital diaphragmatic hernia: Logistic regression analysis-Mortality and extracorporeal membrane oxygenation                                                                          | RADIOLOGY                                         | 62            | 2008 | 12.1          | 25.8         |
| 8    | Zhou et al.      | Ensembled deep learning model outperforms human experts in diagnosing biliary atresia from sonographic gallbladder images                                                                                        | NATURE COMMUNICATIONS                             | 56            | 2021 | 14.7          | 5.4          |
| 9    | Rayan et al.     | Binomial Classification of Pediatric Elbow Fractures Using a Deep Learning Multiview Approach Emulating Radiologist Decision Making                                                                              | RADIOLOGY-ARTIFICIAL INTELLIGENCE                 | 52            | 2019 | 8.1           | 9.6          |
| 10   | Chong et al.     | Predictive modeling in pediatric traumatic brain injury using machine learning                                                                                                                                   | BMC MEDICAL RESEARCH METHODOLOGY                  | 50            | 2015 | 3.9           | 18.0         |
| 11   | Xiao et al.      | Follow the Sound of Children's Heart: A Deep-Learning-Based Computer-Aided Pediatric CHDs Diagnosis System                                                                                                       | IEEE INTERNET OF THINGS JOURNAL                   | 46            | 2020 | 8.2           | 8.7          |
| 12   | Dupuis et al.    | External validation of a commercially available deep learning algorithm for fracture detection in children                                                                                                       | DIAGNOSTIC AND INTERVENTIONAL IMAGING             | 43            | 2022 | 4.9           | 4.7          |
| 13   | Ren et al.       | Maternal exposure to ambient PM10 during pregnancy increases the risk of congenital heart defects: Evidence from machine learning models                                                                         | SCIENCE OF THE TOTAL ENVIRONMENT                  | 39            | 2018 | 8.2           | 15.4         |
| 14   | Quon et al.      | Deep Learning for Pediatric Posterior Fossa Tumor Detection and Classification: A Multi-Institutional Study                                                                                                      | AMERICAN JOURNAL OF NEURORADIOLOGY                | 38            | 2020 | 3.1           | 10.5         |
| 15   | Chen et al.      | CT-Based Radiomics Signature With Machine Learning Predicts MYCN Amplification in Pediatric Abdominal Neuroblastoma                                                                                              | FRONTIERS IN ONCOLOGY                             | 36            | 2021 | 3.5           | 8.3          |
| 16   | Attallah         | MB-AI-His: Histopathological Diagnosis of Pediatric Medulloblastoma and its Subtypes via AI                                                                                                                      | DIAGNOSTICS                                       | 35            | 2021 | 3             | 8.6          |
| 17   | Peng et al.      | Deep learning-based automatic tumor burden assessment of pediatric high-grade gliomas, medulloblastomas, and other leptomeningeal seeding tumors                                                                 | NEURO-ONCOLOGY                                    | 33            | 2022 | 16.4          | 6.1          |
| 18   | Reismann et al.  | Diagnosis and classification of pediatric acute appendicitis by artificial intelligence methods: An investigator-independent approach                                                                            | PLOS ONE                                          | 33            | 2019 | 2.9           | 15.2         |

(Continued)

TABLE 1 Continued

| Rank | Author                 | Title                                                                                                                                                                            | Journal                                                           | Citations (N) | Year | Impact factor | Impact index |
|------|------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------|---------------|------|---------------|--------------|
| 19   | García-Cano et al.     | Prediction of spinal curve progression in Adolescent Idiopathic Scoliosis using Random Forest regression                                                                         | COMPUTERS IN BIOLOGY AND MEDICINE                                 | 33            | 2018 | 7             | 18.2         |
| 20   | Salekin et al.         | Multimodal spatio-temporal deep learning approach for neonatal postoperative pain assessment                                                                                     | COMPUTERS IN BIOLOGY AND MEDICINE                                 | 32            | 2021 | 7             | 9.4          |
| 21   | Tajdari et al.         | Image-based modelling for Adolescent Idiopathic Scoliosis: Mechanistic machine learning analysis and prediction                                                                  | COMPUTER METHODS IN APPLIED MECHANICS AND ENGINEERING             | 32            | 2021 | 6.9           | 9.4          |
| 22   | Zhang et al.           | Clinical application of artificial intelligence-assisted diagnosis using anteroposterior pelvic radiographs in children with developmental dysplasia of the hip                  | BONE & JOINT JOURNAL                                              | 32            | 2020 | 4.9           | 12.5         |
| 23   | Zhou et al.            | Automatic Machine Learning to Differentiate Pediatric Posterior Fossa Tumors on Routine MR Imaging                                                                               | AMERICAN JOURNAL OF NEURORADIOLOGY                                | 32            | 2020 | 3.1           | 12.5         |
| 24   | Karimi-Bidhendi et al. | Fully-automated deep-learning segmentation of pediatric cardiovascular magnetic resonance of patients with complex congenital heart diseases                                     | JOURNAL OF CARDIOVASCULAR MAGNETIC RESONANCE                      | 29            | 2020 | 4.2           | 13.8         |
| 25   | Wadhvani et al.        | Predicting ideal outcome after pediatric liver transplantation: An exploratory study using machine learning analyses to leverage Studies of Pediatric Liver Transplantation Data | PEDIATRIC TRANSPLANTATION                                         | 29            | 2019 | 1.2           | 17.2         |
| 26   | Nurmaini et al.        | Deep Learning-Based Computer-Aided Fetal Echocardiography: Application to Heart Standard View Segmentation for Congenital Heart Defects Detection                                | SENSORS                                                           | 28            | 2021 | 3.4           | 10.7         |
| 27   | Lv et al.              | Artificial intelligence-assisted auscultation in detecting congenital heart disease                                                                                              | EUROPEAN HEART JOURNAL—DIGITAL HEALTH                             | 28            | 2021 | 4             | 10.7         |
| 28   | Bertsimas et al.       | Comparison of Machine Learning Optimal Classification Trees With the Pediatric Emergency Care Applied Research Network Head Trauma Decision Rules                                | JAMA PEDIATRICS                                                   | 28            | 2019 | 24.7          | 17.9         |
| 29   | Irles et al.           | Estimation of Neonatal Intestinal Perforation Associated with Necrotizing Enterocolitis by Machine Learning Reveals New Key Factors                                              | INTERNATIONAL JOURNAL OF ENVIRONMENTAL RESEARCH AND PUBLIC HEALTH | 28            | 2018 | NA            | 21.4         |
| 30   | Zheng et al.           | The impact of pharmacogenomic factors on steroid dependency in pediatric heart transplant patients using logistic regression analysis                                            | PEDIATRIC TRANSPLANTATION                                         | 28            | 2004 | 1.2           | 71.4         |
| 31   | DiRusso et al.         | Development of a model for prediction of survival in pediatric trauma patients: Comparison of artificial neural networks and logistic regression                                 | JOURNAL OF PEDIATRIC SURGERY                                      | 28            | 2002 | 2.4           | 78.6         |
| 32   | Lure et al.            | Using machine learning analysis to assist in differentiating between necrotizing enterocolitis and spontaneous intestinal perforation: A novel predictive analytic tool          | JOURNAL OF PEDIATRIC SURGERY                                      | 27            | 2021 | 2.4           | 11.1         |
| 33   | Attallah et al.        | AI-Based Pipeline for Classifying Pediatric Medulloblastoma Using Histopathological and Textural Images                                                                          | LIFE-BASEL                                                        | 25            | 2022 | 3.2           | 8.0          |
| 34   | Marcinkevics et al.    | Using Machine Learning to Predict the Diagnosis, Management and Severity of Pediatric Appendicitis                                                                               | FRONTIERS IN PEDIATRICS                                           | 25            | 2021 | 2.1           | 12.0         |
| 35   | Arafati et al.         | Artificial intelligence in pediatric and adult congenital cardiac MRI: an unmet clinical need                                                                                    | CARDIOVASCULAR DIAGNOSIS AND THERAPY                              | 25            | 2019 | 2             | 20.0         |
| 36   | Aydin et al.           | A novel and simple machine learning algorithm for preoperative diagnosis of acute appendicitis in children                                                                       | PEDIATRIC SURGERY INTERNATIONAL                                   | 24            | 2020 | 1.5           | 16.7         |
| 37   | Huang et al.           | Artificial Intelligence Applications in Pediatric Brain Tumor Imaging: A Systematic Review                                                                                       | WORLD NEUROSURGERY                                                | 23            | 2022 | 1.9           | 8.7          |
| 38   | Quon et al.            | Artificial intelligence for automatic cerebral ventricle segmentation and volume calculation: a clinical tool for the evaluation of pediatric hydrocephalus                      | JOURNAL OF NEUROSURGERY-PEDIATRICS                                | 23            | 2021 | 2.1           | 13.0         |

(Continued)

TABLE 1 Continued

| Rank | Author               | Title                                                                                                                                                                                                                        | Journal                                                  | Citations (N) | Year | Impact factor | Impact index |
|------|----------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------|---------------|------|---------------|--------------|
| 39   | Daldrup-Link         | Artificial intelligence applications for pediatric oncology imaging                                                                                                                                                          | PEDIATRIC RADIOLOGY                                      | 23            | 2019 | 2.1           | 21.7         |
| 40   | Bartz-Kurycki et al. | Enhanced neonatal surgical site infection prediction model utilizing statistically and clinically significant variables in combination with a machine learning algorithm                                                     | AMERICAN JOURNAL OF SURGERY                              | 23            | 2018 | 2.7           | 26.1         |
| 41   | Hayashi et al.       | Automated detection of acute appendicular skeletal fractures in pediatric patients using deep learning                                                                                                                       | SKELETAL RADIOLOGY                                       | 22            | 2022 | 1.9           | 9.1          |
| 42   | Zeng et al.          | Explainable machine-learning predictions for complications after pediatric congenital heart surgery                                                                                                                          | SCIENTIFIC REPORTS                                       | 22            | 2021 | 3.8           | 13.6         |
| 43   | Bertsimas et al.     | Adverse Outcomes Prediction for Congenital Heart Surgery: A Machine Learning Approach                                                                                                                                        | WORLD JOURNAL FOR PEDIATRIC AND CONGENITAL HEART SURGERY | 22            | 2021 | 1.1           | 13.6         |
| 44   | Jalali et al.        | Machine Learning Applied to Registry Data: Development of a Patient-Specific Prediction Model for Blood Transfusion Requirements During Craniofacial Surgery Using the Pediatric Craniofacial Perioperative Registry Dataset | ANESTHESIA AND ANALGESIA                                 | 22            | 2021 | 4.6           | 13.6         |
| 45   | Truong et al.        | Application of machine learning in screening for congenital heart diseases using fetal echocardiography                                                                                                                      | INTERNATIONAL JOURNAL OF CARDIOVASCULAR IMAGING          | 21            | 2022 | 1.5           | 9.5          |
| 46   | Tunthanathip et al.  | Comparison of intracranial injury predictability between machine learning algorithms and the nomogram in pediatric traumatic brain injury                                                                                    | NEUROSURGICAL FOCUS                                      | 21            | 2021 | 3.3           | 14.3         |
| 47   | Killian et al.       | Machine learning-based prediction of health outcomes in pediatric organ transplantation recipients                                                                                                                           | JAMIA OPEN                                               | 21            | 2021 | 2.5           | 14.3         |
| 48   | Toba et al.          | Prediction of Pulmonary to Systemic Flow Ratio in Patients With Congenital Heart Disease Using Deep Learning-Based Analysis of Chest Radiographs                                                                             | JAMA CARDIOLOGY                                          | 21            | 2020 | 14.7          | 19.0         |
| 49   | Choi et al.          | Deep Learning-Assisted Diagnosis of Pediatric Skull Fractures on Plain Radiographs                                                                                                                                           | KOREAN JOURNAL OF RADIOLOGY                              | 20            | 2022 | 4.4           | 10.0         |
| 50   | Mullen et al.        | Race and Genetics in Congenital Heart Disease: Application of iPSCs, Omics, and Machine Learning Technologies                                                                                                                | FRONTIERS IN CARDIOVASCULAR MEDICINE                     | 20            | 2021 | 2.8           | 15.0         |
| 51   | Day et al.           | Artificial intelligence, fetal echocardiography, and congenital heart disease                                                                                                                                                | PRENATAL DIAGNOSIS                                       | 20            | 2021 | 2.7           | 15.0         |
| 52   | Dhaliwal et al.      | Accurate Classification of Pediatric Colonic Inflammatory Bowel Disease Subtype Using a Random Forest Machine Learning Classifier                                                                                            | JOURNAL OF PEDIATRIC GASTROENTEROLOGY AND NUTRITION      | 20            | 2021 | 2.4           | 15.0         |
| 53   | Lin et al.           | Interpretable prediction of necrotizing enterocolitis from machine learning analysis of premature infant stool microbiota                                                                                                    | BMC BIOINFORMATICS                                       | 19            | 2022 | 2.9           | 10.5         |
| 54   | Liu et al.           | Deep learning-based computer-aided heart sound analysis in children with left-to-right shunt congenital heart disease                                                                                                        | INTERNATIONAL JOURNAL OF CARDIOLOGY                      | 19            | 2022 | 3.2           | 10.5         |
| 55   | Shi et al.           | Explainable machine learning model for predicting the occurrence of postoperative malnutrition in children with congenital heart disease                                                                                     | CLINICAL NUTRITION                                       | 19            | 2022 | 6.6           | 10.5         |
| 56   | Tunthanathip et al.  | Application of machine learning to predict the outcome of pediatric traumatic brain injury                                                                                                                                   | CHINESE JOURNAL OF TRAUMATOLOGY                          | 19            | 2021 | 1.8           | 15.8         |
| 57   | Kwong et al.         | Posterior Urethral Valves Outcomes Prediction (PUVOP): a machine learning tool to predict clinically relevant outcomes in boys with posterior urethral valves                                                                | PEDIATRIC NEPHROLOGY                                     | 19            | 2022 | 2.6           | 10.5         |
| 58   | Diller et al.        | Denosing and artefact removal for transthoracic echocardiographic imaging in congenital heart disease: utility of diagnosis specific deep learning algorithms                                                                | INTERNATIONAL JOURNAL OF CARDIOVASCULAR IMAGING          | 19            | 2019 | 1.5           | 26.3         |

(Continued)

TABLE 1 Continued

| Rank | Author              | Title                                                                                                                                                                                               | Journal                                                  | Citations (N) | Year | Impact factor | Impact index |
|------|---------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------|---------------|------|---------------|--------------|
| 59   | Blazadonakis et al. | Deep assessment of machine learning techniques using patient treatment in acute abdominal pain in children                                                                                          | ARTIFICIAL INTELLIGENCE IN MEDICINE                      | 19            | 1996 | 6.1           | 147.4        |
| 60   | Qu et al.           | Using Innovative Machine Learning Methods to Screen and Identify Predictors of Congenital Heart Diseases                                                                                            | FRONTIERS IN CARDIOVASCULAR MEDICINE                     | 18            | 2022 | 2.8           | 11.1         |
| 61   | Wang et al.         | Application of deep learning upon spinal radiographs to predict progression in adolescent idiopathic scoliosis at first clinic visit                                                                | ECLINICALMEDICINE                                        | 18            | 2021 | 9.6           | 16.7         |
| 62   | Chang et al.        | Improving preoperative risk-of-death prediction in surgery congenital heart defects using artificial intelligence model: A pilot study                                                              | PLOS ONE                                                 | 18            | 2020 | 2.9           | 22.2         |
| 63   | Jalali et al.       | Prediction of Periventricular Leukomalacia in Neonates after Cardiac Surgery Using Machine Learning Algorithms                                                                                      | JOURNAL OF MEDICAL SYSTEMS                               | 18            | 2018 | 3.5           | 33.3         |
| 64   | Fernandez et al.    | Digital Pattern Recognition for the Identification and Classification of Hypospadias Using Artificial Intelligence vs. Experienced Pediatric Urologist                                              | UROLOGY                                                  | 17            | 2021 | 2.1           | 17.6         |
| 65   | Hoodbhoy et al.     | Diagnostic Accuracy of Machine Learning Models to Identify Congenital Heart Disease: A Meta-Analysis                                                                                                | FRONTIERS IN ARTIFICIAL INTELLIGENCE                     | 17            | 2021 | 3             | 17.6         |
| 66   | Rani et al.         | Predicting congenital heart disease using machine learning techniques                                                                                                                               | JOURNAL OF DISCRETE MATHEMATICAL SCIENCES & CRYPTOGRAPHY | 17            | 2020 | 1.2           | 23.5         |
| 67   | Thomford et al.     | Implementing Artificial Intelligence and Digital Health in Resource-Limited Settings? Top 10 Lessons We Learned in Congenital Heart Defects and Cardiology                                          | OMICS-A JOURNAL OF INTEGRATIVE BIOLOGY                   | 17            | 2020 | 2.2           | 23.5         |
| 68   | Nagy et al.         | A pediatric wrist trauma x-ray dataset (GRAZPEDWRI-DX) for machine learning                                                                                                                         | SCIENTIFIC DATA                                          | 16            | 2022 | 5.8           | 12.5         |
| 69   | Liu et al.          | Incorporating Radiomics into Machine Learning Models to Predict Outcomes of Neuroblastoma                                                                                                           | JOURNAL OF DIGITAL IMAGING                               | 16            | 2022 | 2.9           | 12.5         |
| 70   | Cirillo et al.      | Improving burn depth assessment for pediatric scalds by AI based on semantic segmentation of polarized light photography images                                                                     | BURNS                                                    | 16            | 2021 | 3.2           | 18.8         |
| 71   | Pasha et al.        | Machine Learning Predicts the 3D Outcomes of Adolescent Idiopathic Scoliosis Surgery Using Patient-Surgeon Specific Parameters                                                                      | SPINE                                                    | 16            | 2021 | 2.7           | 18.8         |
| 72   | Peng et al.         | Prediction of Proximal Junctional Kyphosis After Posterior Scoliosis Surgery With Machine Learning in the Lenke 5 Adolescent Idiopathic Scoliosis Patient                                           | FRONTIERS IN BIOENGINEERING AND BIOTECHNOLOGY            | 16            | 2020 | 4.3           | 25.0         |
| 73   | Yin et al.          | Multi-instance Deep Learning of Ultrasound Imaging Data for Pattern Classification of Congenital Abnormalities of the Kidney and Urinary Tract in Children                                          | UROLOGY                                                  | 16            | 2020 | 2.1           | 25.0         |
| 74   | Malek et al.        | Random forest and Self Organizing Maps application for analysis of pediatric fracture healing time of the lower limb                                                                                | NEUROCOMPUTING                                           | 16            | 2018 | 5.5           | 37.5         |
| 75   | Steyaert et al.     | Multimodal deep learning to predict prognosis in adult and pediatric brain tumors                                                                                                                   | COMMUNICATIONS MEDICINE                                  | 15            | 2023 | 5.4           | 6.7          |
| 76   | Zech et al.         | Detecting pediatric wrist fractures using deep-learning-based object detection                                                                                                                      | PEDIATRIC RADIOLOGY                                      | 15            | 2023 | 2.1           | 6.7          |
| 77   | Zhang et al.        | Diagnostic Accuracy of 3D Ultrasound and Artificial Intelligence for Detection of Pediatric Wrist Injuries                                                                                          | CHILDREN-BASEL                                           | 15            | 2021 | 2             | 20.0         |
| 78   | Koller et al.       | Accurate prediction of spontaneous lumbar curve correction following posterior selective thoracic fusion in adolescent idiopathic scoliosis using logistic regression models and clinical rationale | EUROPEAN SPINE JOURNAL                                   | 15            | 2019 | 2.6           | 33.3         |
| 79   | Maggio et al.       | Distillation of the clinical algorithm improves prognosis by multi-task deep learning in high-risk Neuroblastoma                                                                                    | PLOS ONE                                                 | 15            | 2018 | 2.9           | 40.0         |

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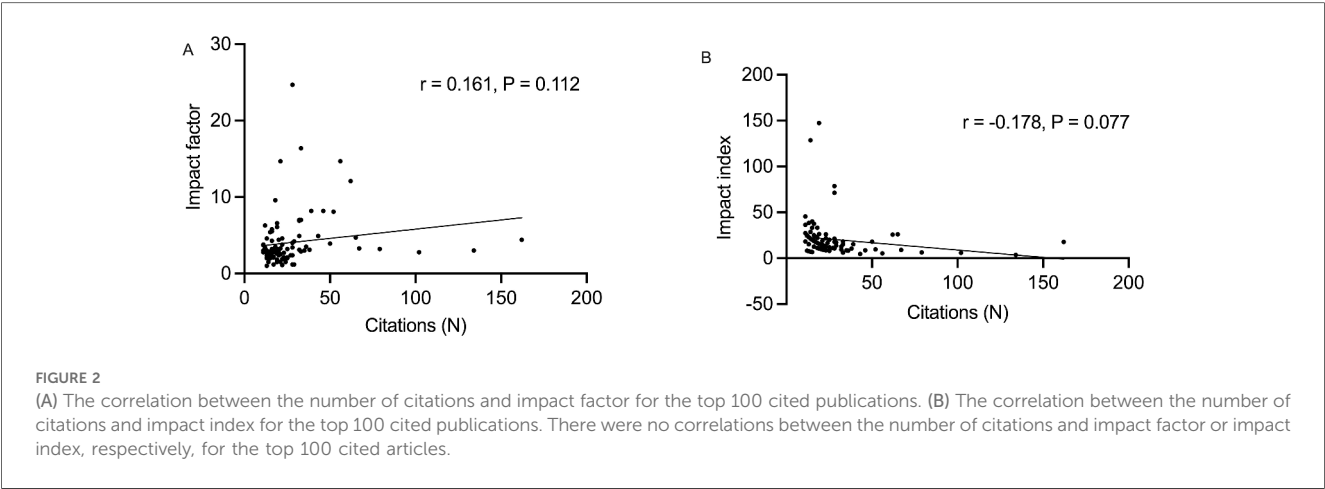
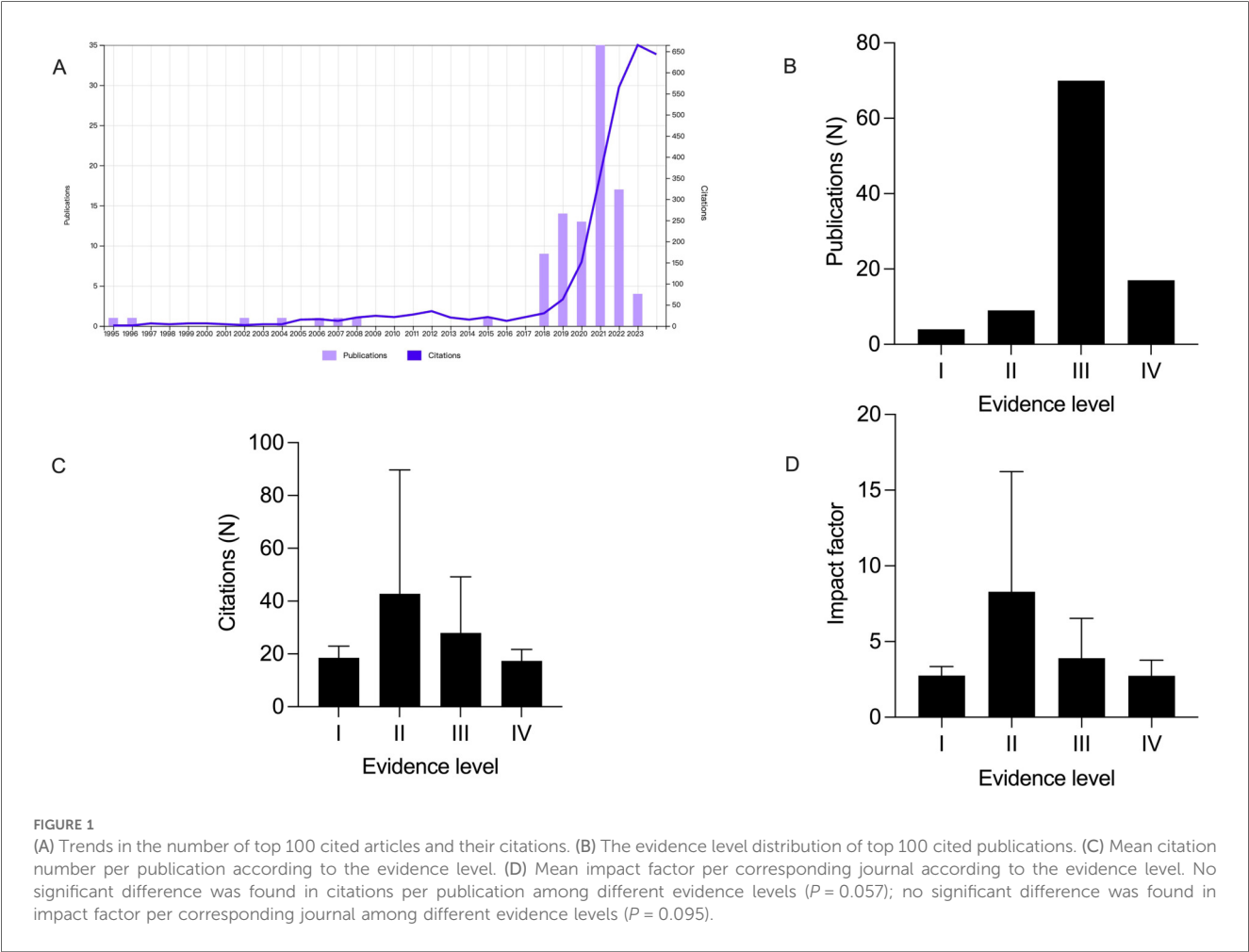
TABLE 1 Continued

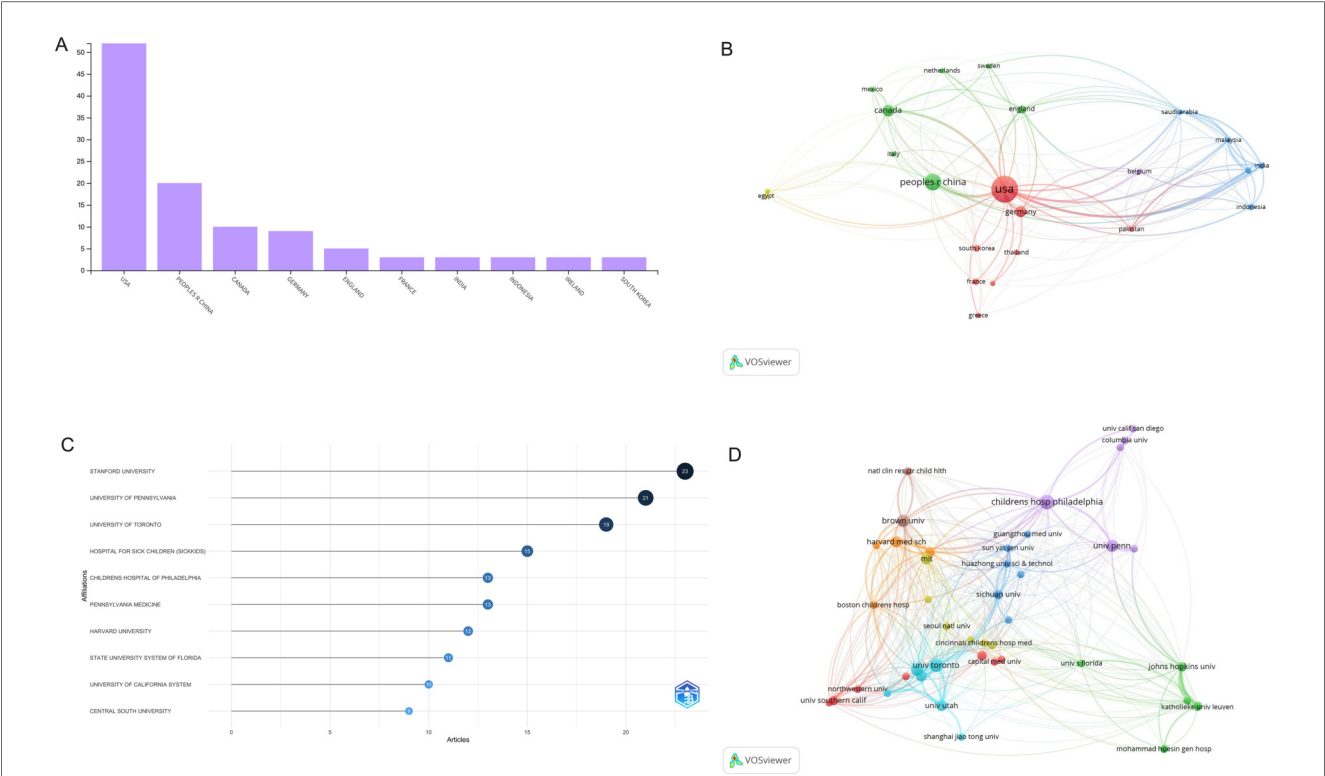
| Rank | Author                | Title                                                                                                                                                                  | Journal                                          | Citations (N) | Year | Impact factor | Impact index |
|------|-----------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------|---------------|------|---------------|--------------|
| 80   | Das et al.            | Exercise capacity in pediatric heart transplant candidates: Is there any role for the 14 ml/kg/min guideline?                                                          | PEDIATRIC CARDIOLOGY                             | 14            | 2006 | 1.5           | 128.6        |
| 81   | Xiao et al.           | Revolutionizing Healthcare with ChatGPT: An Early Exploration of an AI Language Model's Impact on Medicine at Large and its Role in Pediatric Surgery                  | JOURNAL OF PEDIATRIC SURGERY                     | 14            | 2023 | 2.4           | 7.1          |
| 82   | Shahi et al.          | Decision-making in pediatric blunt solid organ injury: deep learning approach to predict massive transfusion, need for operative management, and mortality risk        | JOURNAL OF PEDIATRIC SURGERY                     | 14            | 2021 | 2.4           | 21.4         |
| 83   | Stiel et al.          | The Modified Heidelberg and the AI Appendicitis Score Are Superior to Current Scores in Predicting Appendicitis in Children: A Two-Center Cohort Study                 | FRONTIERS IN PEDIATRICS                          | 14            | 2020 | 2.1           | 28.6         |
| 84   | Van den Eynde et al.  | Artificial intelligence in pediatric cardiology: taking baby steps in the big world of data                                                                            | CURRENT OPINION IN CARDIOLOGY                    | 13            | 2022 | 2             | 15.4         |
| 85   | Mohsin et al.         | The Role of Artificial Intelligence in Prediction, Risk Stratification, and Personalized Treatment Planning for Congenital Heart Diseases                              | CUREUS JOURNAL OF MEDICAL SCIENCE                | 13            | 2023 | 1             | 7.7          |
| 86   | Sethi et al.          | Artificial Intelligence in Pediatric Cardiology: A Scoping Review                                                                                                      | JOURNAL OF CLINICAL MEDICINE                     | 13            | 2022 | 3             | 15.4         |
| 87   | Xu et al.             | A Deep-Learning Aided Diagnostic System in Assessing Developmental Dysplasia of the Hip on Pediatric Pelvic Radiographs                                                | FRONTIERS IN PEDIATRICS                          | 13            | 2022 | 2.1           | 15.4         |
| 88   | Feng et al.           | Prediction for Mitosis-Karyorrhexis Index Status of Pediatric Neuroblastoma via Machine Learning Based 18F-FDG PET/CT Radiomics                                        | DIAGNOSTICS                                      | 13            | 2022 | 3             | 15.4         |
| 89   | Wang et al.           | Characteristics of Fecal Microbiota and Machine Learning Strategy for Fecal Invasive Biomarkers in Pediatric Inflammatory Bowel Disease                                | FRONTIERS IN CELLULAR AND INFECTION MICROBIOLOGY | 13            | 2021 | 4.6           | 23.1         |
| 90   | van den Eynde et al.  | Medicine-Based Evidence in Congenital Heart Disease: How Artificial Intelligence Can Guide Treatment Decisions for Individual Patients                                 | FRONTIERS IN CARDIOVASCULAR MEDICINE             | 13            | 2021 | 2.8           | 23.1         |
| 91   | Gómez-Quintana et al. | A Framework for AI-Assisted Detection of Patent Ductus Arteriosus from Neonatal Phonocardiogram                                                                        | HEALTHCARE                                       | 13            | 2021 | 2.4           | 23.1         |
| 92   | Bertsimas et al.      | Prediction of cervical spine injury in young pediatric patients: an optimal trees artificial intelligence approach                                                     | JOURNAL OF PEDIATRIC SURGERY                     | 13            | 2019 | 2.4           | 38.5         |
| 93   | Haldar et al.         | Unsupervised machine learning using K-means identifies radiomic subgroups of pediatric low-grade gliomas that correlate with key molecular markers                     | NEOPLASIA                                        | 12            | 2023 | 6.3           | 8.3          |
| 94   | Amodeo et al.         | A maChine and deep Learning Approach to predict pulmoNary hypertenSion in newbornS with congenital diaphragmatic Hernia (CLANNISH): Protocol for a retrospective study | PLOS ONE                                         | 12            | 2021 | 2.9           | 25.0         |
| 95   | Gao et al.            | Multimodal AI System for the Rapid Diagnosis and Surgical Prediction of Necrotizing Enterocolitis                                                                      | IEEE ACCESS                                      | 12            | 2021 | 3.4           | 25.0         |
| 96   | Nurmaini et al.       | Deep Learning for Improving the Effectiveness of Routine Prenatal Screening for Major Congenital Heart Diseases                                                        | JOURNAL OF CLINICAL MEDICINE                     | 11            | 2022 | 3             | 18.2         |
| 97   | Herz et al.           | Segmentation of Tricuspid Valve Leaflets From Transthoracic 3D Echocardiograms of Children With Hypoplastic Left Heart Syndrome Using Deep Learning                    | FRONTIERS IN CARDIOVASCULAR MEDICINE             | 11            | 2021 | 2.8           | 27.3         |
| 98   | Kwon et al.           | Deep learning algorithms for detecting and visualising intussusception on plain abdominal radiography in children: a retrospective multicenter study                   | SCIENTIFIC REPORTS                               | 11            | 2020 | 3.8           | 36.4         |
| 99   | Kim et al.            | Performance of deep learning-based algorithm for detection of ileocolic intussusception on abdominal radiographs of young children                                     | SCIENTIFIC REPORTS                               | 11            | 2019 | 3.8           | 45.5         |

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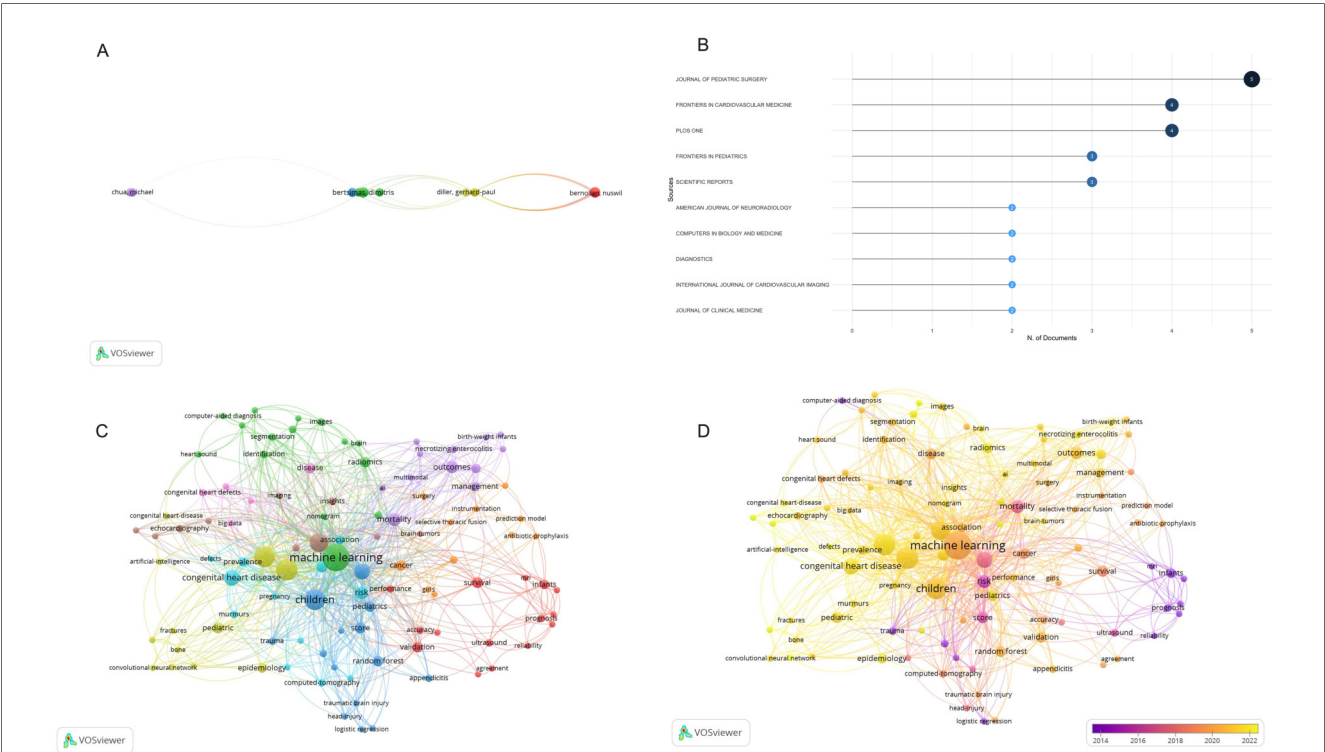
TABLE 1 Continued

| Rank | Author     | Title                                                                                                                        | Journal                                      | Citations (N) | Year | Impact factor | Impact index |
|------|------------|------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------|---------------|------|---------------|--------------|
| 100  | Liu et al. | Mining patient-specific and contextual data with machine learning technologies to predict cancellation of children’s surgery | INTERNATIONAL JOURNAL OF MEDICAL INFORMATICS | 11            | 2019 | 3.7           | 45.5         |





**FIGURE 3** (A) Top 10 authorship countries by the number of publications. (B) Bibliographic coupling analysis of country-wise collaboration. (C) Top 10 authorship organizations by the number of publications. (D) Bibliographic coupling analysis of organization collaboration network.



**FIGURE 4** (A) Co-authorship collaboration network of authors. (B) Top 10 journals by the number of publications. (C) Mapping on co-occurrence of keywords for the top 100 cited articles. (D) Time visualization for the keywords. Keywords in yellow appeared later than that in purple.

## 4 Discussion

With the advent of digital time, it is crucial for scholars to entirely grasp the development in their research fields. Our study used a bibliometric method to investigate the present status and future trends of AI application in pediatric surgery. Unlike systematic review or meta-analysis, the bibliometric method applies visual software such as VOSviewer or bibliometrix package from Rstudio to analyze current publications in detail, in order to reveal research focus and predict trends.

For these 100 impactful publications in this field. The annual article production has presented a general rising trend from 1995 to 2023. Remarkably, the period between 2018 and 2021 witnessed a pivotal boost in AI technologies, including DL, ML and ChatGPT. This technological growth has provided extraordinary opportunities for the diagnosis, treatment and prediction of patients. These findings indicated the enhanced focus and interests from academia on AI application in pediatric surgery research, which was analogous to several other research fields (18, 19).

The USA stood out in the position for the number of articles, which was similar with other medical areas such as robotic arthroplasty and esophageal atresia (14, 20). This phenomenon is probably owing to the advanced technology and robust national support in the USA. In addition, previous literature has suggested that authors from the USA prefer to publish and cite native sources (21, 22). Remarkably, the government of USA issued an executive order titled “Maintaining American Leadership in Artificial Intelligence” mandating all federal government agencies to execute strategic goals for keeping the leading position in AI field on February 11, 2019 (18). Although China started later in AI field, it has become the second most productive country in the world, establishing close collaboration with the USA and Germany based on our country-wise collaboration map. Seven out of the top 10 publishing organizations were from the USA, two were from Canada and the other one was from China, which also indicated the dominant role of the USA in AI. Several findings can be drawn from the organization and country collaboration network in our study. The USA primarily collaborated with China and Germany, while other European countries tended to cooperate more with European Union countries. The USA and China owned both high scientific production and efficient collaboration, while other countries such as India, Indonesia and South Korea maintained considerable scientific outputs with relatively poor global cooperation. The challenges of global collaboration, such as time, cost, and integration, are likely responsible for this. Yet, there are mutual advantages to promote global collaborative efforts, including wider patient recruitment, better generalizability of results, scientific progress, and greater citation impact (23, 24). Collaboration at the global level should take place through international partnerships that lead and encourage action on health concerns by scheduling, support, and technical assistance (25). Due to the centrality of Bertsimas D. from Massachusetts Institute of Technology and Arafati A. from University of California, they were placed as the top authors in publication

and worldwide collaboration field respectively. Studying their scientific outputs would be beneficial to understand of the knowledge structure in this area. The *Journal of Pediatric Surgery* dominated a higher publication count than other journals. Although the IF of the *Journal of Pediatric Surgery* is not the highest, due to it is one of the few journals which focus on pediatric surgery specifically, it contributed the highest number of publications. Researchers concentrating on AI application in pediatric surgery might pay more attention to this source.

Information analysis for the impactful articles is an advantageous index for bibliometric study, which is broadly utilized in various subjects (26, 27). The most cited article in the present analysis was published in 1995 by Peterson et al. in *Journal of Bone and Joint Surgery-American Volume*, predicting the progression of the curve in girls who had adolescent idiopathic scoliosis of moderate severity by using logistic regression analysis (16). The paper with the lowest impact index was released in 2019 by Hauptmann A et al. in the journal *Magnetic Resonance in Medicine*, investigating the potential of deep learning (DL) to reconstruct highly accelerated radial real-time data in patients with congenital heart disease (CHD) (17).

In the field of AI application in pediatric surgery, ML, AI, DL, children and CHD were identified highly frequent mentioned keywords according to the co-occurrence visualization analysis. ML and DL, as subsets of AI, they are especially effective for distinguishing subtle patterns among huge files that is probably imperceptible to humans using conventional statistical methods conducting manual investigations. They have been widely applied to analyze patient data for predicting outcomes and recovery times after surgery, the aim is to provide a better patient care as well as enhance the precision and efficacy of surgical procedures furtherly (28, 29). Notably, CHD was a hotspot in both current research and future trends, its prenatal diagnosis and postnatal management has progressed considerably with the AI assistance (30). Notwithstanding many advantages including precise prenatal screening, improved perioperative planning, acceptable individualized risk stratification and prognostication, a notable challenge for using AI in CHD has been the disconnect between clinical investigators and computer engineers (31). Therefore, computer engineers are necessary to be more familiar with clinical practice. In the meantime, clinicians lack of experience in AI filed shall get more information to better understand how AI works in medicine.

The level of evidence for a certain paper is probably an excellent index to evaluate its scientific quality (32). In the top 100 articles with the highest number of citations on AI application in pediatric surgery, publications with high evidence levels (level I and II), i.e., meta-analysis and prospective study, were underrepresented. For assessing the CHD diagnostic accuracy of ML models, one meta-analysis included 16 studies on 1,217 participants used ML algorithm to diagnose CHD, reporting ML models owned the potential to diagnose CHD correctly without the requirement for experienced personnel. However, the heterogeneity of the CHD diagnosis among these 16 studies was hard to ignore, which was a main limitation (33). One RCT used data from 964 pediatric patients with minor

traumatic brain injury to compare the prediction function between ML and a nomogram, concluding that ML had the superior predictive performance which can assist clinicians with reducing the overuse of head CT scans and therapy costs of pediatric traumatic brain injury (34). The majority of the top 100 cited manuscripts were retrospective studies, which was vital in making research on manifestations and results for diverse cases. Nevertheless, their academic quality is limited: Several information might be lacking, selection and recall deviations can influence the outcomes, and reasons for differences in therapy procedure or inadequate follow-ups cannot be confirmed usually (35). Hence, to enhance the development of AI application in pediatric surgery, prospective studies and RCTs, as the superior standard of scientific work, are needed to a further step.

## 5 Limitations

Inevitably, there are still several limitations in the present study. Firstly, only the WoSCC database was applied to search for relevant studies, therefore, other sources such as Google Scholar or PubMed might have presented a different number of publication items or citations. To improve the comprehensiveness and representativeness of the analysis, we plan to include more data sources in future research. Secondly, only particular papers (English writing, article or review) were included, which may neglect several outstanding literatures published in different languages and cause biased outcomes. Thirdly, we aimed to obtain only related articles on AI application in pediatric surgery, thus the searching strategy of “title” instead of “topic” was utilized. This strategy could probably exclude few, but an insignificant number of pertinent literatures.

## 6 Conclusions

In conclusion, the present study performs the first comprehensive bibliometric analysis of impactful articles pertaining to AI application in pediatric surgery from 1995 to 2023. The USA and China lead the research frontiers, providing valuable opportunities for global cooperations. However, collaborations among developing countries need to be strengthen intensely. Necrotizing enterocolitis, CHD and radiomics might dominate potential hotspots in the future. This study may play a helpful role for researchers studying on AI application in pediatric surgery by providing insights into potential collaboration and prospects for future research.

## 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

BS: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft. SZ: Methodology, Visualization, Writing – review & editing. JG: Methodology, Visualization, Writing – review & editing. LW: Methodology, Visualization, Writing – review & editing. XW: Methodology, Supervision, Visualization, Writing – review & editing.

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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.

## Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

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