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Twelve-year global publications on small incision lenticule extraction: A bibliometric analysis

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Purpose: To analyze the development process of small incision lenticule extraction (SMILE) surgery in a 12-year period.

Methods: We conducted a literature search for SMILE research from 2011 to 2022 using the Science Citation Index Expanded (SCIE) of the Web of Science Core Collection (WoSCC). The VOS viewer, and CiteSpace software were used to perform the bibliometric analysis. Publication language, annual growth trend, countries/regions and institutions, journals, keywords, references, and citation bursts were analyzed.

Results: A total of 731 publications from 2011 to 2022 were retrieved. Annual publication records grew from two to more than 100 during this period. China had the highest number of publications (n = 326). Sixty-five keywords that appeared more than four times were classified into six clusters: femtosecond laser technology, dry eye, biomechanics, visual quality, complications, and hyperopia.

Conclusion: The number of literatures has been growing rapidly in the past 12 years. Our study provides a deep insight into publications on SMILE for researchers and clinicians with bibliometric analysis for the first time.

KEYWORDS

bibliometric analysis, small incision lenticule extraction, SMILE, femtosecond laser technology, complications

Introduction

Small incision lenticule extraction (SMILE) is the newest laser vision correction procedure, where the refractive lenticule cut by a femtosecond laser is extracted through a small corneal incision (1). The basic principle of SMILE surgery is similar to that of traditional corneal refractive surgery, which corrects myopia by changing the corneal curvature. The most creative design of SMILE surgery involves a small incision. Coincidentally, the 2-mm incision at the edge also resembles a smile. SMILE surgery evolved from femtosecond lenticule extraction (FLEx). Thanks to the precise resection obtained by the femtosecond laser technique, FLEx was first introduced at the American Academy of Ophthalmology Annual Meeting in 2006 by Walter Sekundo and Marcus Blum, and was first reported by Walter Sekundo et al. (2). Subsequently, researchers found that a more minimally invasive surgery can be achieved by a small surgical incision. The earliest pieces of literature on SMILE surgery were published by Walter Sekundo et al. and Rupal Shah et al. (3, 4). At present, SMILE surgery has gradually become one of the most widely used corneal refractive surgeries. Like a single spark that could kindle a whole prairie, the evolution of SMILE surgery over the past 12 years has been drastic. Currently, the number of SMILE surgeries has reached six million globally. A large number of studies on this surgery have also been published.

Bibliometrics involve scientific summarization of the literature through intuitive charts, which makes it easy to understand the countries, institutions, authors, journals, and hotspots of related disciplines. This study aimed to analyze the research progress in SMILE surgery over the last 12 years through bibliometrics.

Materials and methods

Data source

We conducted a literature search for SMILE research from 2011 to 2022 using the Science Citation Index-Expanded (SCIE) of the Web of Science Core Collection (WoSCC) to identify SMILE-related publications, limited to "article" and "review", over the past 12 years (from 2011 to 2022) with no language restriction. Our search strategy was as follows: Topic = ("small incision lenticule extraction" OR "small incision lenticule extractions" OR SMILE*). All retrieved records were downloaded on May 14, 2022.

Statistical analysis

The annual number of publications, type of documents, and languages on SMILE studies were analyzed using CiteSpace 6.2.1 (Drexel University, Philadelphia, PA, United States). The impact factors of the journals were provided by the 2021 Journal Citation Reports (Clarivate Analytics, Philadelphia, PA, United States). Elements of SMILE research, including countries/regions, keywords, journals, and main co-cited journals, were identified via VOS viewer 1.6.15 (Leiden University, Leiden, Netherlands). A publication was assigned equally to all participating countries/regions or institutions when it was completed by collaborations between more than one country/region or institution. Network maps for countries/regions, institutions, journals, and the main co-cited journals were generated by the VOS viewer in addition to cluster analysis and density maps for high-frequency keywords. On the bibliometric maps generated by the VOS viewer, different nodes represent elements, and the larger the size of the node, the higher the number or frequency of elements is. A line, which connects two nodes, reflects the relationship between different elements, and its thickness indicates the strength of the relationship. Nodes of different colors represent different clusters. Parameters of the VOS viewer were set as follows: fractional counting at the counting method, ignoring documents with too many authors (maximum number of authors per document: 25). Microsoft Office Excel 2019 (Redmond, Washington, United States) was used to manage data. The correlation between the year and the number of articles was expressed by the linear correlation coefficient (R^2).

Results

In total, 731 publications associated with SMILE in the WoSCC from 2011 to 2022 were identified (**Figure 1**), of which, 667 (91.24%) and 64 (8.76%) were indexed as "article" and "review," respectively.

Annual growth trend

Outputs of the annual publication with an upward trend are shown in **Figure 2**. There were two and four papers published in 2011 and 2012, respectively. The number of publications was 61 in 2015, which increased to more than 80 in 2017, and reached the highest in 2020 ($n = 120$). A significant correlation between the number of studies and the year of publication was found with a high coefficient of determination ($R^2 = 0.62$).

Countries/regions and institutions analysis

The top 10 countries or regions, and institutions among the 604 institutions in 45 countries are shown in **Table 1**, according to the number of publications.

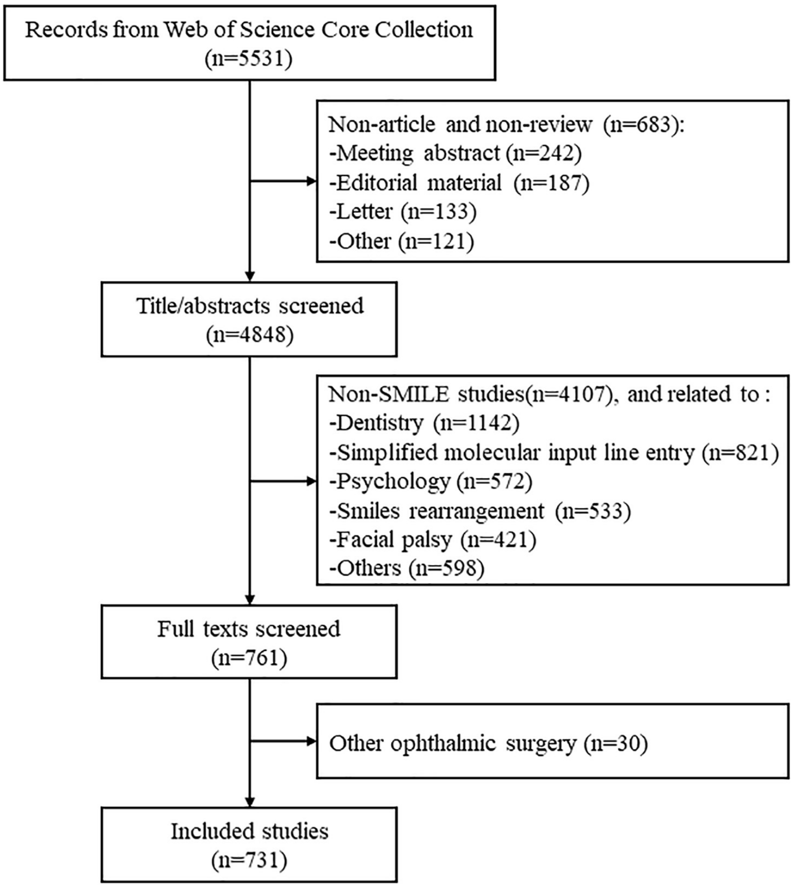

FIGURE 1
Results of literature search.

A total of 45 countries/regions contributed to SMILE research. China published the highest number of papers (*n* = 326), followed by the United States (*n* = 140), Germany (*n* = 81), India (*n* = 68), and France (*n* = 58). As shown in **Figure 3A**, the annual output of most countries showed an upward trend. All countries/regions were used to construct a country/region network map (**Figure 3B**).

The top 10 institutions were distributed in five countries/regions, four of which were in China (**Table 1**). As **Figure 3C** shows, institutions (70/604, 11.59%) with six or more (T = 6) publications were used to construct the co-authorship network. The institutions were then divided into six clusters of different colors.

Journal analysis

Seventy-seven scholarly journals published papers on SMILE research. Over 250 papers were published in the top two journals, both of which were published in the United States (**Table 2**). The *Journal of Refractive Surgery* published the most papers (*n* = 166), followed by the *Journal of Cataract and Refractive Surgery* (*n* = 98), and *BMC Ophthalmology* (*n* = 48). Among 1144 co-cited academic journals, five had more than 1000 citations, and all of them were from the United States. The *Journal of Refractive Surgery* had the most co-citations (*n* = 4427), followed by the *Journal of Cataract and Refractive Surgery* (*n* = 3928), *Investigative Ophthalmology & Visual Science* (*n* = 1252), *Cornea* (*n* = 1217), and *Ophthalmology* (*n* = 1155).

Journals (36/77, 46.75%) with a publication number greater than or equal to three (T = 3) were used to construct the citation network map, which can be divided into five clusters with different colors (**Figure 4A**).

Journals (65/1144, 5.68%) with co-citations greater than or equal to 25 (T = 25) were used to construct the co-citation network (**Figure 4B**).

Keywords analysis

A total of 686 hotspot keywords for SMILE research were extracted with a frequency of occurrence of 1720. Subsequently,

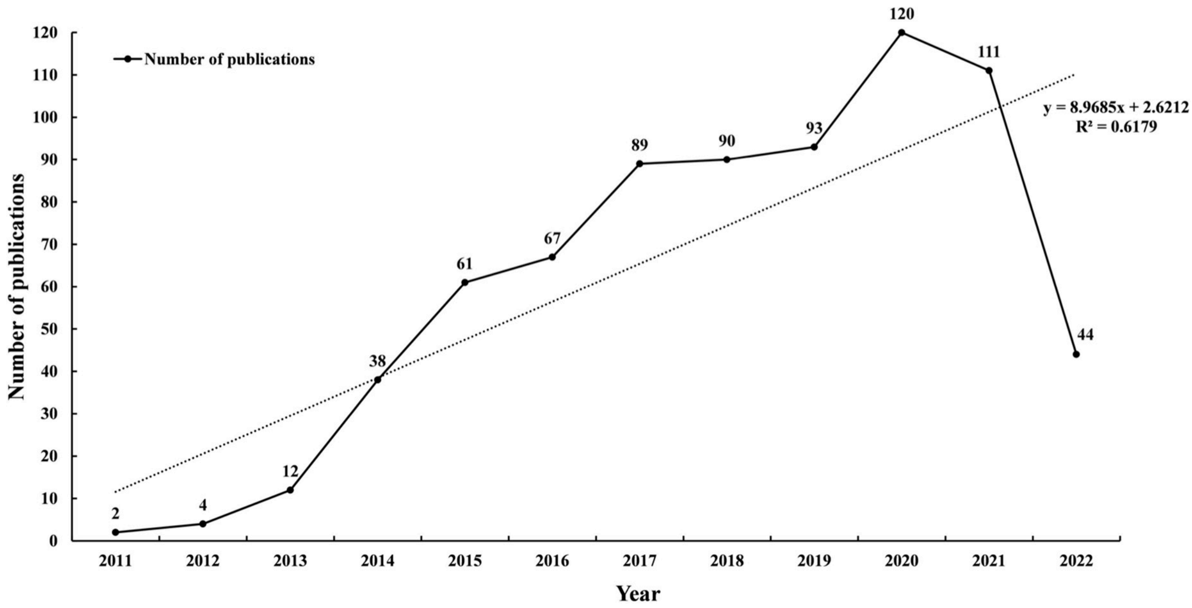

FIGURE 2
The number of publications per year (2011–2022).

TABLE 1 The top 10 most productive countries/regions and institution for SMILE research.

Rank	Country/region	*N* (%)	Rank	Institution	*N* (%)
1	China (Asia)	326 (44.60)	1	Fudan University	103 (14.09)
2	United States (North America)	140 (19.15)	2	Tianjin Medical University	51 (6.98)
3	Germany (Europe)	81 (12.37)	3	Sun Yat-sen University	43 (5.88)
4	India (Asia)	68 (9.30)	4	Singapore National Eye Centre	42 (5.75)
5	France (Europe)	58 (7.93)	5	Duke-NUS Medical School	39 (5.34)
6	United Kingdom (Europe)	58 (7.93)	6	Singapore Eye Research Institute	39 (5.34)
7	Singapore (Asia)	46 (6.29)	7	London Vision Clinic	37 (5.06)
8	South Korea (Asia)	39 (5.34)	8	Shanghai Research Center of Ophthalmology and Optometry	37 (5.06)
9	Spain (Europe)	36 (4.92)	9	Columbia University	35 (4.79)
10	Denmark (Europe)	32 (4.38)	10	Aarhus University Hospital	28 (3.83)

65 keywords that appeared more than four times were included and classified into six clusters on the map (**Figure 5**), including cluster 1 (biomechanics, collagen cross-linking, in red), cluster 2 (ectasia and corneal topography, in green), cluster 3 (dry eye and corneal sensation, in blue), cluster 4 (visual quality, glare, and astigmatism, in yellow), cluster 5 (complication and femtosecond laser, in purple), and cluster 6 (hyperopia and intraocular pressure, in bright blue).

Reference analysis

The top 10 co-cited references in SMILE research are listed in **Table 3**. Each reference was co-cited at least 93 times.

Citation bursts

The top 25 citation bursts pertaining to the development of SMILE were identified from 2011 to 2022 (**Table 4**). The increasing number of citations of these papers in a certain period indicated rapid dissemination. Among them, the first citation burst appeared in 2011, while the last eight citation bursts began after 2020.

Discussion

Bibliometrics is helpful for understanding the evolutionary process of a discipline. Through keyword analysis, we found

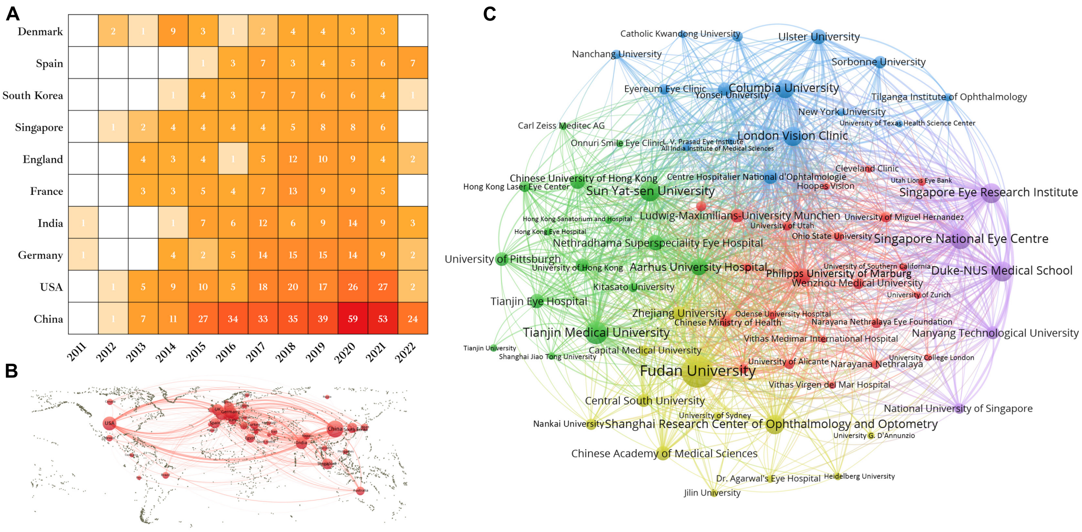

FIGURE 3
The annual output of publications in the top 10 countries/regions **(A)**, the network map of countries/regions **(B)**, and institutions **(C)** related to SMILE research.

TABLE 2 The top 10 productive journals and co-cited journals of SMILE research.

Rank	Journal	N	IF2021[a]	Q[b]	Co-cited journal	Co-citation	IF2021	Q
1	Journal of Refractive Surgery (United States)	166	3.255	Q2	Journal of Refractive Surgery (United States)	4427	3.255	Q2
2	Journal of Cataract and Refractive Surgery (United States)	98	3.528	Q2	Journal of Cataract and Refractive Surgery (United States)	3928	3.528	Q2
3	BMC Ophthalmology (England)	48	2.090	Q3	Investigative Ophthalmology & Visual Science (United States)	1252	4.925	Q1
4	Cornea (United States)	42	3.152	Q2	Cornea (United States)	1217	3.152	Q2
5	Journal of Ophthalmology (United States)	29	1.974	Q4	Ophthalmology (United States)	1155	14.277	Q1
6	PLoS One (United States)	23	3.752	Q2	British Journal of Ophthalmology (England)	913	5.915	Q1
7	Indian Journal of Ophthalmology (India)	18	2.969	Q3	American Journal of Ophthalmology (United States)	774	5.488	Q1
8	International Journal of Ophthalmology (China)	18	1.647	Q4	Graefes Archive for Clinical and Experimental Ophthalmology (United States)	627	3.535	Q2
9	Graefes Archive for Clinical and Experimental Ophthalmology (United States)	17	3.535	Q2	PLoS One (United States)	527	3.752	Q2
10	International Ophthalmology (Netherlands)	17	2.029	Q3	Clinical Ophthalmology (England)	367	-	-

[a]Impact factor of the journals that was provided by the 2021 Journal Citation Report. [b]Quartile in category that was provided by the 2021 Journal Citation Reports.

that the research keywords for SMILE surgery can be classified into six clusters: femtosecond laser technology, dry eye, biomechanics, visual quality, complications, and hyperopia. These keywords reflect the main concerns of clinicians and researchers regarding the development of SMILE surgery. Thus, we have discussed the development of SMILE in the following order: basic information and six clusters.

Basic information

Studies on SMILE surgery peaked in 2020. The number of articles published in various countries is mostly on the rise, indicating the rapid development of SMILE. Among them, China has the largest number of papers. This may be due to an early start of SMILE surgery in China. Currently, SMILE

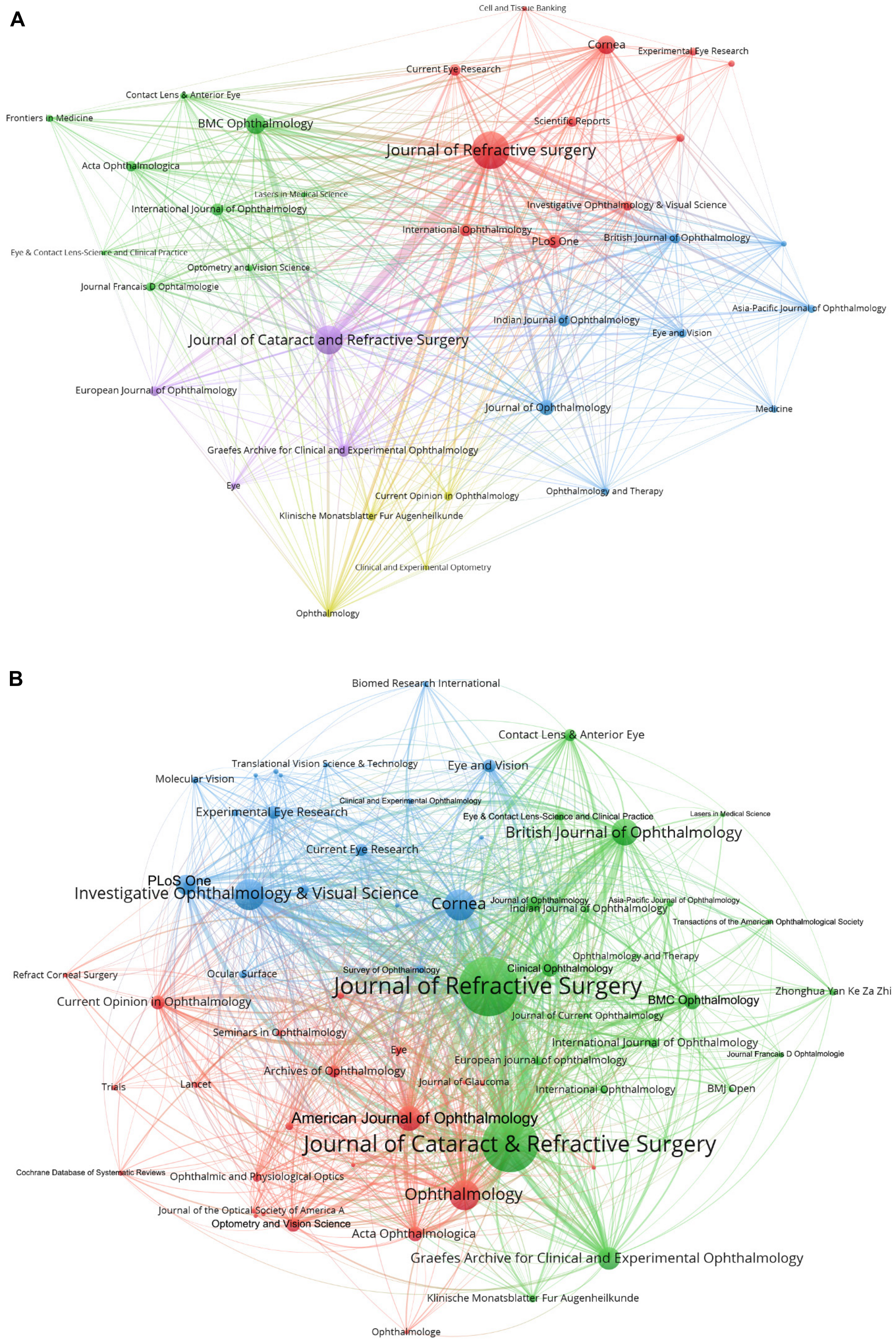

FIGURE 4
The network map of scholarly journals **(A)** and co-cited scholarly journals **(B)** for SMILE research.

has become the most common corneal surgical method for myopia correction in China, and more than three million SMILE surgeries have been completed in China. Therefore, it is not surprising to find that Chinese research institutions occupy the top four of 10 seats with good international collaboration. The United States is potent enough to mention here, as SMILE surgery was approved by the United States Food and Drug Administration (FDA) in 2016 (30). In addition, as shown in **Figure 3B**, a tight collaboration was observed between the United States and China. The *Journal of Refractive Surgery*

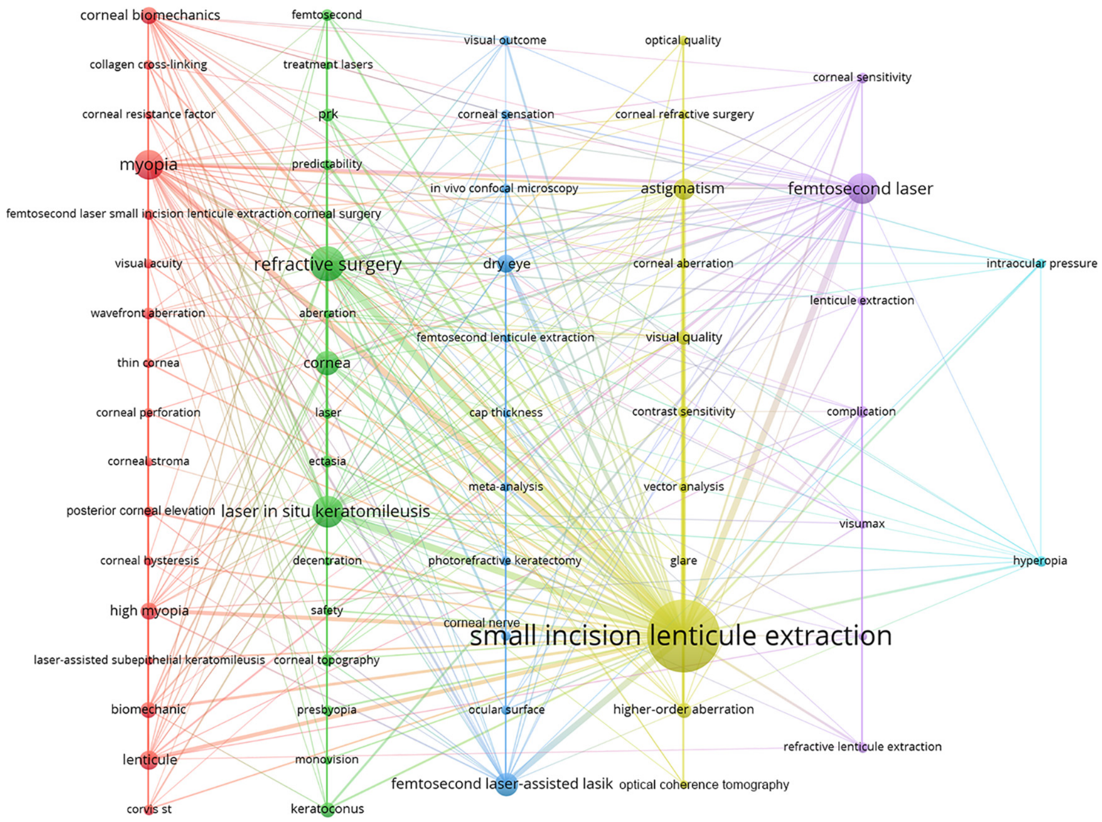

FIGURE 5
The network map of keywords for SMILE research.

and *Journal of Cataract and Refractive Surgery* ranked first and second in the lists of the most productive and co-cited journals, respectively.

Femtosecond laser technology

Owing to the development of femtosecond lasers, corneal laser surgery has entered the femtosecond era. The femtosecond laser replaced the keratome, which was the preferred tool for laser-assisted *in situ* keratomileusis (LASIK) flap making. Thereafter, the FLEx (2) and SMILE surgery (3, 4) came into being, followed by gradual development. The most cited literature in SMILE-related research was published between 2008 and 2014 (**Table 3**). During this period, the surgical technique for SMILE was still in its infancy, and the most important discussion was associated with the predictability and safety of SMILE surgery since they were the focuses of most of the top 10 co-cited studies (3, 4, 6, 8–10, 31).

Furthermore, predictability has remained a hotspot. Initial research focused on early postoperative predictability, but current researchers are more concerned about long-term predictability since five of the 11 top references with the strongest citation bursts in 2022 were focused on this aspect (**Table 4**). Several studies have shown exciting long-term predictivity, stability, safety, and high patient satisfaction (24, 32). This provides clinicians with confidence in SMILE surgery. However, factors related to corneal regression and comparisons between SMILE and other refractive surgeries are worth investigating.

TABLE 3 The top 10 co-cited references in SMILE research.

Rank	References	N
1	Sekundo et al. (3)	371
2	Shah et al. (4)	293
3	Ivarsen et al. (5)	184
4	Vestergaard et al. (6)	140
5	Reinstein et al. (7)	131
6	Sekundo et al. (2)	127
7	Sekundo et al. (8)	113
8	Ganesh and Gupta (9)	109
9	Hjortdal et al. (10)	103
10	Wu et al. (11)	93

TABLE 4 The top 25 references with the strongest citation bursts in the co-citation network.

References	Strength	Begin	End	2011–2022
Blum et al. (12)	21.06	2011	2015	
Sekundo et al. (3)	49.3	2012	2016	
Shah et al. (4)	39.41	2012	2016	
Vestergaard et al. (6)	17.2	2012	2017	
Ang et al. (13)	10.54	2012	2015	
Hjortdal et al. (10)	12.84	2013	2017	
Riau et al. (14)	12.45	2013	2016	
Vestergaard et al. (15)	8.1	2013	2014	
Kamiya et al. (16)	7.01	2013	2015	
Wei et al. (17)	6.87	2013	2015	
Tay et al. (18)	6.31	2013	2015	
Shah et al. (4)	8.99	2014	2016	
Gertnere et al. (19)	6.89	2014	2015	
Reinstein et al. (7)	6.26	2014	2017	
Shetty et al. (20)	8.64	2019	2022	
Ganesh et al. (21)	7.58	2019	2022	
Zhang et al. (22)	7.48	2019	2022	
Blum et al. (23)	15.41	2020	2022	
Han et al. (24)	10.41	2020	2022	
Kim et al. (1)	10.09	2020	2022	
Li et al. (25)	8.64	2020	2022	
Titiyal et al. (26)	8.48	2020	2022	
Han et al. (27)	8.41	2020	2022	
Wang et al. (28)	8.11	2020	2022	
Daingaard et al. (29)	6.71	2020	2022	

The red line means strong citation burst timeline, while the blue line means infrequent citation timeline.

Biomechanics

Since the incision of SMILE is small, another interest is whether fewer changes in corneal biomechanics occur during SMILE surgery. Researchers have compared biomechanical results of SMILE and LASIK using dynamic Scheimpflug imaging (Corvis ST) (20, 33), Ocular Response Analyzer (ORA) (34), mathematical analyses (7, 35), as well as meta-analysis (36), and demonstrated that SMILE seems to be superior to LASIK in terms of preserving corneal biomechanics. However, common problems of corneal refractive surgery, such as refractive regression and postoperative corneal ectasia, still cannot be avoided in SMILE surgery. Nineteen cases of corneal ectasia after SMILE surgery have been reported since 2017, although the previous tomography findings were not normal in some of these cases. Based on the literature review of ectasia, the incidence of post-refractive ectasia in eyes without identifiable preoperative risk factors is 20 per 100,000 eyes for photorefractive keratectomy (PRK), 90 per 100,000 eyes for LASIK, and 11 per 100,000 eyes for SMILE (37). In addition, it is believed that the combination of Corvis ST and Pentacam can fill the void in preoperative risk prediction and early diagnosis of corneal ectasia and keratoconus; however, the data output by Corvis ST still warrants further discussion.

Visual quality

The visual quality of SMILE surgery has been widely studied. Aberration is the most commonly used method for evaluating visual quality. Many studies have shown that a smaller spherical aberration was induced by SMILE compared to LASIK (24, 38, 39), which might be due to the larger optical zone after SMILE (24). With the emergence of new detection methods, results of the visual quality of SMILE surgery using methods such as optical quality assessment system (OQAS) (40, 41), Oculus Cataract Quantifier (C-Quant) (42), disk halo sizes (43), and corneal densitometry (44) have been reported successively. The overall trend indicates that SMILE surgery has no significant impact on visual quality three months postoperatively. No significant difference in corneal transparency has been shown in the first postoperative week (44).

Astigmatism is another important research topic. Unlike LASIK, in which an infrared-guided pupil tracking system is used during the surgical process, SMILE mainly depends on the surgeon's judgment. Consequently, the comparison of astigmatism vector analysis between the two surgeries has attracted much attention. Although there is no unified conclusion at present, it is reported that there is slight inferiority and more under-correction during SMILE than during LASIK when treating low-to-moderate astigmatism, and a comparable rate of under-correction when treating high astigmatism (45, 46). Comparing outcomes of astigmatism correction of SMILE surgery with those of other surgical methods, as well as different types of astigmatism correction, need to be studied. In addition, software that enhances eye tracking or cyclotorsion compensation is also being developed and will soon be available (1).

Complications

Complications of SMILE are a constant concern, especially postoperative complications such as corneal ectasia. Other common postoperative complications include dry eyes and diffuse lamellar keratitis (47).

Initially, intraoperative complications gained more attention than postoperative ones, as a certain learning curve is required for surgeons performing SMILE. In 2014, Ivarsen et al. (5) published a study based on clinical results and surgical complications of more than 1,500 SMILE operations. This article is also the third in the top co-cited references in SMILE-related research and the first clinical practice result for SMILE with a large sample. In this study, tearing at the incision (114/1800) and difficulties in lenticule separation (34/1800) are common causes of intraoperative complications. Other common intraoperative complications include suction loss, opaque bubble layer (OBL), and black spots (47). In the initial period of the learning curve for SMILE, some patients may experience delayed vision recovery, although the phenomenon may be improved by lowering the femtosecond laser energy and advancing the surgical experience (48). In general, SMILE is associated with rapid visual recovery, and most patients can achieve 20/20 visual acuity within one day after surgery according to our and other surgeons' experience (49).

Dry eye

The main highlight of SMILE is the characteristic small incision. Compared to the approximately 20 mm incision in LASIK, a small incision design guarantees a reduction in flap-related complications, such as flap loss and flap displacement. In addition, it also reduces damage to the corneal nerves. Compared with LASIK, the recovery time of corneal sensation and dry eye symptoms after SMILE has been proved to be shortened through clinical research and experimental research (50, 51).

Hyperopia

Treatment of hyperopia with SMILE is not easy. The result of the earliest attempt using FLEx was not satisfactory. By enlarging the transition zone in SMILE, its stability is improved, and the refractive outcomes are similar to those of LASIK (52, 53). At present, global clinical observation of hyperopia SMILE has led to preliminary results, and it is believed that hyperopia SMILE will be progressing in the next few years (54).

For correction of hyperopia, an important and attractive surgical correction is the transplantation of lenticules obtained from the SMILE procedure (55). Lenticule keratophakia and epikeratophakia are reversible in SMILE, and the visual quality offers unique advantages (56, 57). Moreover, the discarded tissue was also reused as a bio-scaffold for stromal engineering, and an ocular drug delivery system of active molecules (58, 59).

Conclusion

The number of literature has been growing rapidly in the past 12 years. Our study provides a deep insight into publications on SMILE for researchers and clinicians with bibliometric analysis for the first time.

Data availability statement

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

Author contributions

TH and XZ: conceptualization. LZ: data curation. TH and LZ: writing original draft preparation. All authors: reviewing and 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.

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