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REVIEW

A Two-Decade Bibliometric Analysis of Laser in Ophthalmology: From Past to Present

Yaping Jiang[1,*], Yuying Cai[1,*], Xin Zhang[1], Li Chen[1], Xingtao Zhou[2], Yihui Chen[1]

[1]Department of Ophthalmology, Yangpu Hospital, School of Medicine, Tongji University, Shanghai, People's Republic of China; [2]Eye Institute and Department of Ophthalmology, Institute for Medical and Engineering Innovation, Eye & ENT Hospital, Fudan University; NHC Key Laboratory of Myopia (Fudan University), Key Laboratory of Myopia, Chinese Academy of Medical Sciences, Shanghai, People's Republic of China

*These authors contributed equally to this work

Correspondence: Xingtao Zhou, Eye Institute and Department of Ophthalmology, Institute for Medical and Engineering Innovation, Eye & ENT Hospital, Fudan University; NHC Key Laboratory of Myopia (Fudan University), Key Laboratory of Myopia, Chinese Academy of Medical Sciences, No. 19 Baoqing Road, Xuhui District, Shanghai, 200031, People's Republic of China, Email doctzhouxingtao@163.com; Yihui Chen, Department of Ophthalmology, Yangpu Hospital, School of Medicine, Tongji University, 450 Tengyue Road, Shanghai, 200090, People's Republic of China, Email 1300089@tongji.edu.cn

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Background: Laser therapy has been proven as an effective technique for managing ophthalmological disorders. To guide future research, we conducted a bibliometric analysis of laser applications in eye diseases from 1990 to 2022, aiming to identify key themes and trends.

Methods: We retrieved 3027 publications from the Web of Science Core Collection (WoSCC). Bibliometrix was used for science mapping of the literature, while VOSviewer and CiteSpace were applied to visualize co-authorship, co-citation, co-occurrence, and bibliographic coupling networks.

Results: From a co-citation reference network, we identified 52 distinct clusters. Our analysis uncovered three main research trends. The first trend revolves around the potential evolution of corneal laser surgery techniques, shifting from the treatment of refractive errors to broader applications in biomedical optics. The second trend illustrates the advancement of laser applications in treating a range of disorders, from retinal and ocular surface diseases to glaucoma. The third trend focuses on the innovative uses of established technologies.

Conclusion: This study offers significant insights into the evolution of laser applications in ophthalmology over the past 30 years, which will undoubtedly assist scientists in directing further research in this promising field.

Keywords: laser, bibliometric, research trend, systematic review, CiteSpace

Introduction

Laser in Retinal Diseases

Laser, known as Light Amplification by Stimulated Emission of Radiation, is a coherent, focused, monochromatic, high-energy light. Since its initial use on the retina in 1961,[1] laser surgery has gained widespread acceptance and use in ophthalmology because it is more versatile, precise, and has fewer complications than conventional surgery. Nowadays, a variety of common ocular illnesses are treated with lasers. Since the late 1960s, choroidal neovascularization secondary to age-related macular degeneration and retinal fissures that can result in retinal detachment have been widely treated using argon blue-green laser. According to guidelines published by the Diabetic Retinopathy Study (DRS) and the Early Treatment of Diabetic Retinopathy Study (ETDRS), argon laser photocoagulation has become the gold standard for the treatment of Proliferative Diabetic Retinopathy (PDR). Patients with diabetic retinopathy can undergo Panretinal Photocoagulation (PRP) using both krypton red and argon lasers. The aim of laser (mainly argon laser) in PRP treatment is to destroy areas where capillary non-perfusion and retinal ischemia exist and decrease metabolism and oxygen consumption in the outer layers, allowing for a greater supply of nutrients and oxygen to the inner layers of the retina.

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In fact, numerous landmark studies have confirmed that laser PRP is effective for reducing vision loss. DRS showed that laser photocoagulation of the retina reduced severe vision loss (defined as visual acuity of 5/200 or less with a time interval of at least four months),[2] and that focal or grid photocoagulation was beneficial in reducing vision loss due to macular edema.[3] Lesions close to the macula are more suited for treatment with the krypton red laser because the macular region absorbs yellow-green light.

Laser in Glaucoma and Cataract

Laser techniques, including argon laser selective laser trabeculoplasty (SLT), Neodymium-doped Yttrium Aluminium Garnet (Nd:YAG) laser iridotomy, and the latter used in early glaucoma. Laser therapy is a crucial component of glaucoma treatment for managing intraocular pressure.

The Nd:YAG laser has been widely used in removing lens capsule due to the high accessibility of near-infrared light to the lens and lens capsule. Nd:YAG laser posterior capsulotomy is the most common and probably the most successful application. With few complications, the Nd:YAG laser has a great track record of enhancing visual acuity. The Nd:YAG laser eliminates the requirement for surgical capsulotomy, which raises the risk of vitreous and intraocular lens (IOL) displacement, macular cystoid edema, and retinal detachment.

Laser in Corneal Refractive Surgery

The excimer laser is a precisely focused and controlled ultraviolet beam that uses excited argon fluoride gas to emit a cold laser at 193 nm in the far ultraviolet spectrum. This allows for accurate cutting of tissue without damage. The excimer laser has the unique advantage of a low cutting threshold, neat cutting edges, and minimal damage to adjacent tissues. In 1991, the excimer laser was approved by the US Food and Drug Administration (FDA) and has since been used for the treatment of refractive errors. Laser refractive keratectomy (PRK), ethanol-based excimer laser epithelial flap under keratomileusis (LASEK), mechanical excimer laser epithelial flap under keratomileusis (Epi-LASIK), and trans-epithelial laser keratomileusis (Trans PRK) have been performed since then. In 1998, the development of femtosecond laser animal experiments marked a new era of refractive surgery. With the FDA approval of femtosecond laser for clinical use in 2010, femtosecond laser-assisted LASIK (FS-LASIK) and femtosecond laser small incision lenticule extraction (SMILE) appeared. In addition, due to the emergence of refractive surgery and technological innovation, it has also led to the study of intraocular lens (IOL) calculation formula for cataract surgery and biomechanical changes.

In recent years, due to the rapid development of laser technology, several systematic reviews and meta-analyses have been published for comprehensive summaries. However, most of them focus on a particular disease, such as laser in diabetic retinopathy, indicating the need for new methods to review and analyze the trends in this field. Scientometrics, or bibliometrics applied to scientific research, allows us to summarize large amounts of bibliometric data to demonstrate the state of knowledge and emerging trends in a research field over time. Scientometrics includes phylograms and bibliometric analysis. Phylograms enable visualization and mapping of the evolution of research over time. The bibliometric analysis measures correlations of evidence and the impact of authors through performance analysis and bibliometric mapping. This approach combines statistical and mathematical methods with data visualization to determine the structure of knowledge, current developments, and research frontiers in a specific field. Bibliometrics is also an important tool for identifying the most influential authors, institutions, countries, and journals within a defined research field. The most common methods of bibliometric analysis include co-authorship analysis, co-occurrence analysis, and co-citation analysis. Co-authorship analysis reveals patterns of collaboration among authors, institutions, and countries. Co-occurrence analysis exploits the frequency of multiple words in the same article to determine their relationship, thus revealing hotspots and trends in the discipline. Co-citation analysis can help researchers discover and identify the knowledge base and development context of the discipline.

We have therefore combined bibliometric analysis and systematic mapping to conduct a scientometric study on ocular laser applications. Our primary aim is to assess the evolution of ocular laser applications over the past decades in terms of research themes and trends. Our secondary aim is to measure research manifestations and relevance in terms of countries, institutions, authors, and journals, and to estimate potential hotspots based on emerging trends.

Methods

Search Strategy and Data Collection

The researchers plan to conduct an extensive search for related publications, encompassing all relevant terms and phrases pertinent to laser use in ophthalmology. Following a meticulous selection and validation of search terms in Web of Science Core Collection (WOSCC), we intend to search WOSCC from inception using a combination of keywords and MeSH terms: ("Surgery, Ocular" OR "Ocular Surgeries" OR "Ocular Surgery" OR "Ophthalmology" OR "Eye Disorder" OR "Eye Disorders" OR "Eye Disease" OR "Eye Diseases") AND laser. A total of 3027 publications, comprising 2721 articles, 276 reviews, 30 editorial materials, and 24 early access pieces, are included in the record. The reasons for excluding certain articles and the extraction procedure, as illustrated in the flowchart in Supplementary Figure 1, are fully described in the Supplemental Material.

Data Analysis and Software

We utilized the Bibliometrix R packages (3.1.4), VOSviewer (1.6.16) (van Eck and Waltman, 2010), and CiteSpace (5.8. R3) to conduct the analyses. The bibliometric information of selected publications was collected, including keywords, authors, journals, subject categories, institutions, countries, years of publication, numbers of citations, and reference records.

The bibliometric results included citation counts, co-citation counts, and co-occurrence counts. The number of co-citations is the frequency with which two published articles are cited by a subsequent publication. A co-citation relationship, linking two articles that are simultaneously cited by a third manuscript, results in the formation of a co-citation network. Such a network integrates individual papers to create a representation that can depict significant historical changes and also the evolution of a cluster. A co-occurrence network illustrates how frequently different variables occur together. The process of building this network involves identifying keywords in a text, calculating the frequency of keyword co-occurrence, and identifying clusters of keywords within the network. Systematic mapping provides a picture of the current state of knowledge in the scientific literature. This visual representation, created by clustering co-citations or co-occurrences, can also highlight areas requiring further research. Bibliographic coupling, based on citation sources, develops when two sources frequently cite the same work. Author-document coupling serves as a valuable supplement to author co-citation methods when examining the organization of information within a discipline.

After processing the documents using CiteSpace, several metrics of importance are generated. Key metrics such as Betweenness centrality, which represents the unweighted shortest path between all nodes in the graph determined by the algorithm for that metric, can be used to denote a measure's importance. Nodes with high Betweenness centrality typically connect several clusters and are regarded as crucial hubs. CiteSpace also calculates a sigma score, where a higher score denotes a larger impact, by combining Betweenness centrality as a structural feature with Burstness as a temporal property. The modularity, or Q score, indicates the degree of grouping and ranges from 0 to +1. Graphs with a high Q score contain numerous links within a module but few connections pointing outward. Consistency is measured using the silhouette (S score), a metric ranging from −1 to +1. For both metrics, a score closer to +1 represents the optimal clustering model.

In the VOSviewer visualization graph, each node is represented by a circle with a label. Larger circles indicate a higher frequency in the co-occurrence analysis. The thickness and length of line segments between nodes reflect the strength and relevance of the connections among the corresponding nodes.

Results

Analysis of Co-Cited Reference

Co-Citation Analysis of References

We generated a map of the reference co-citation network (Figure 1). In this network of co-cited references, we identified 56 unique clusters from 1990 to 2022, with significant modularity and silhouette scores indicating highly plausible groupings (Q=0.8828; S=0.9561). Details of the extracted clusters are displayed in Supplementary Figure 2 and Supplementary Table 1.

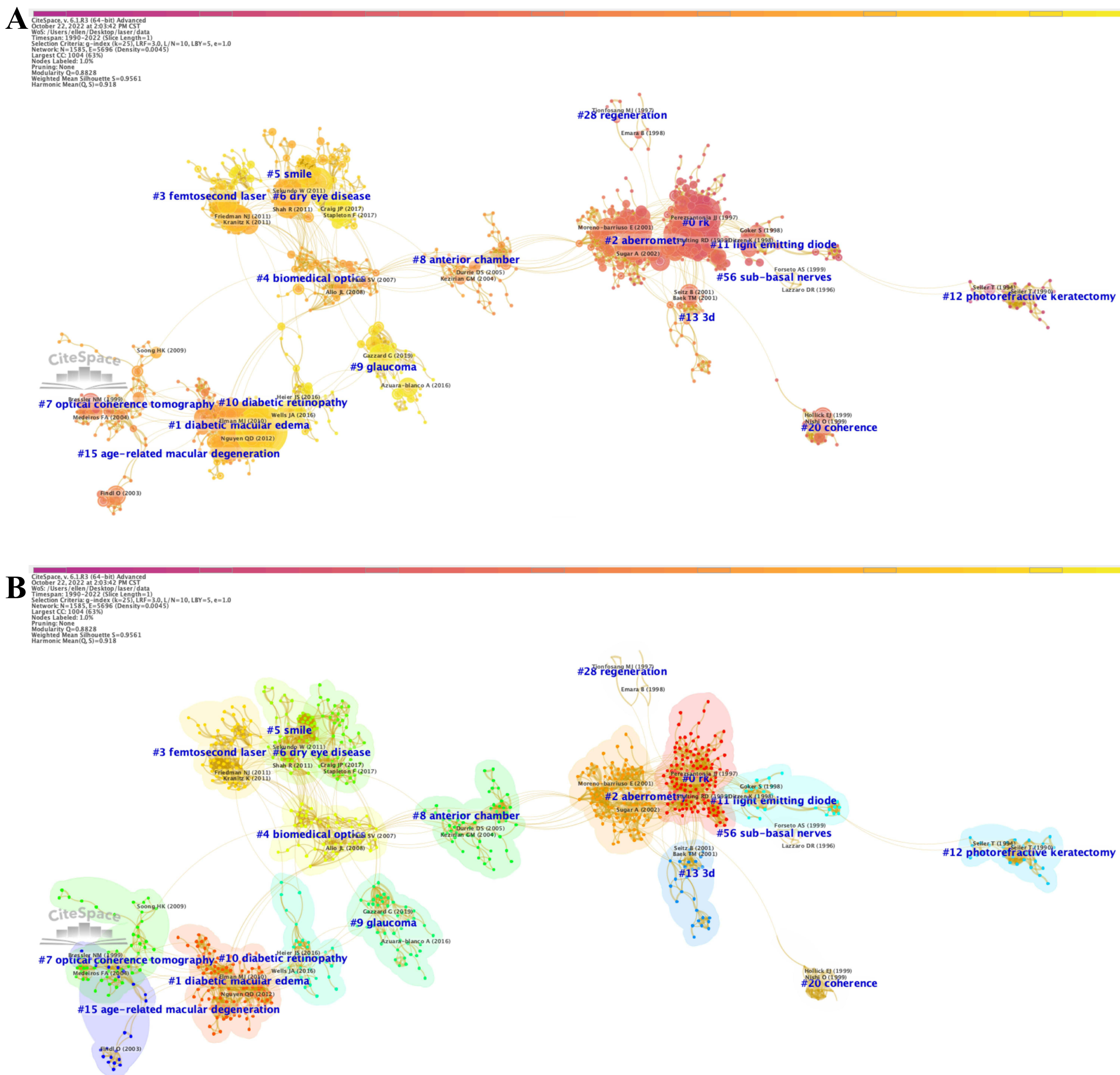

Figure 1 Co-citation references network (1990–2022) and correspondent clustering analysis obtained with CiteSpace. (**A**) Co-citation reference network with cluster visualization and burstness of hotspots. (**B**) Visualization map of the corresponding clusters and burestness of hotspots.
Notes: The size of a node (article) is proportional to the number of times the article has been co-cited. Burstness is represented by red tree rings, with either important citation burst.

The walkthrough of links, from 1990 to 2022, between clusters based on burst dynamics identified two distinct major research trends (available in Supplementary Figure 3). The first major research trend concerns the technological innovation and safety evaluation of lasers in refractive surgery. The first cluster, with an indication of the label, silhouette score, the average year of publication of the cluster members, and the most representative reference, is #12 ("photo-refractive keratectomy"; S=1; 1991), which shared hotspots with cluster #0 ("rk"; S=0.924; 1997). These clusters branched into #11 ("light emitting diode"; S=0.976; 1997) and #2 ("aberrometryaberrometry"; S=0.931; 2001), and eventually developed into cluster #13 ("3d"; S=0.989; 2003) and #8 ("anterior chamber"; S=0.962; 2005). These primarily concern the cluster of the excimer laser until the appearance of cluster #4 ("biomedical optics"; S=0.937; 2008), which signifies a new research field in which optics and life science intersect and permeate each other. This is the application of modern optical technology in the biomedical field. Since then, entirely new technologies have emerged with clusters #3 ("femtosecond laser"; S=0.984; 2014) and #5 ("smile"; S=0.973; 2012), heralding a new era for refractive surgery.

The second major trend of research concerns the specific evolution of diseases in laser applications and began with cluster #15 ("age-related macular degeneration"; S=0.999; 2002). Due to the development and application of optical technology in medicine with cluster #4 ("biomedical optics"; S=0.937; 2008), more technical means have been applied to ophthalmic diseases, such as cluster #1 ("diabetic macular edema"; S=0.967; 2010), cluster #6 ("dry eye disease"; S=0.901; 2015), cluster #9 ("glaucoma"; S=0.943; 2017), and cluster #10 ("diabetic retinopathy"; S=0.975; 2017).

To further examine research trends, we focused on the co-citation reference network for the last five years (2017–2022) and on each month of the last available year (2022) (Supplementary Figure 4A and B). The co-cited reference network was of significant modularity (Q=0.7491) and had a weighted mean silhouette of reasonable quality (S=0.9238). We obtained eight clusters with a significant Q-value and reasonable S-value for all clusters (Supplementary Figure 5 and Supplementary Table 1). In the timeline view (Supplementary Figure 4C), it is easily observed how every single cluster develops over time.

In the early stage, cluster #0 ("phacoemulsification"; S=0.978; 2015), #1 ("diabetic macular edema"; S=0.943; 2014) and #6 ("confocal microscopy"; S=0.872; 2014) appeared first. As time progressed, other clusters gained more attention, with cluster #1 ("diabetic macular edema"; S=0.943; 2014) having the highest frequency and the most bursts, becoming the most active theme. However, we also discovered that the spotlight and research tendency have shifted from cluster #1 ("diabetic macular edema"; S=0.943; 2014) to #2 ("dry eye disease"; S=0.871; 2017) and #3 ("micropulse laser"; S=0.99; 2017).

These clusters represented key research trends. The one trend of the application of lasers in diseases continued to develop with clusters #1 ("diabetic macular edema"; S=0.943; 2014),[4] #2 ("dry eye disease"; S=0.871; 2017)[5] and #4 ("diabetic retinopathy"; S=0.839; 2018).[6]

The another trend of research focused on the modification and updating of the original technology application with clusters #3 ("micropulse laser"; S=0.99; 2017)[7] and #8 ("trabeculectomy"; S=0.989; 2018),[8] which concentrated on the non-invasive surgical treatment of glaucoma. Another minor isolated cluster on the ultrastructure of the cornea is #6 ("confocal microscopy"; S=0.872; 2014).[9]

The third trend concerns the new applications of existing technologies with clusters #5 ("lasik"; S=0.991; 2014)[10] and #0 ("phacoemulsification"; S=0.978; 2015).[11] The combined application of femtosecond laser and phacoemulsification for cataracts was demonstrated.

Most Cited Papers

The most cited papers within each cluster are indeed highly relevant to the topics at hand and provide important insights about the cluster's focus. We have identified the top 10 most co-cited references without any time restriction, which are presented in Table 1.

The first four most cited papers and the last one are randomized controlled trials (RCTs) investigating the comparative efficacy of lasers when used in conjunction with other chemicals in the treatment of diabetic macular edema. These studies were authored by Elman et al,[12] Nguyen et al,[13] Wells et al,[14] and Mitchell et al,[15] and were published in respected journals such as OPHTHALMOLOGY (for the papers by Elman et al, Nguyen et al, and Mitchell et al) and the NEW ENGLAND JOURNAL OF MEDICINE (Wells et al).

The articles ranked 5–9 are prospective studies that discuss the application of lasers in corneal refractive surgery.[16–20] References with citation bursts are those that are cited frequently over a certain period. The duration of these citation bursts is indicated by a red line segment. We have extracted the burst strength and time duration of the top 17 references with the strongest citation bursts from 2017 to 2022, which can be found in Supplementary Table 2.

One notable reference is Brown et al's study on the long-term outcomes of ranibizumab therapy for diabetic macular edema,[21] which saw a significant burst of citations lasting one year. Particularly noteworthy is the TFOS DEWS II Epidemiology Report, published in The Ocular Surface,[22] which had the strongest citation bursts and continued until the end of the period under review.

Table 1 The Top 10 Most Cited References

Number of Citations in the Network	Number of Citations in the Literature	Cited Reference	Year	Source	Vol	Page	Title	Doi	Type of Paper	Related Cluster in Figure 1
40	966	Elman MJ	2010	OPHTHALMOLOGY	117	1064	Randomized Trial Evaluating Ranibizumab Plus Prompt or Deferred Laser or Triamcinolone Plus Prompt Laser for Diabetic Macular Edema	10.1016/j.ophtha.2010.02.031	RCT	1
36	1061	Nguyen QD	2012	OPHTHALMOLOGY	119	789	Ranibizumab for Diabetic Macular Edema Results from 2 Phase III Randomized Trials: RISE and RIDE	10.1016/j.ophtha.2011.12.039	RCT	1
35	992	Wells JA	2015	NEW ENGL J MED	372	1193	Aflibercept, Bevacizumab, or Ranibizumab for Diabetic Macular Edema	10.1056/NEJMoa1414264	RCT	1
27	938	Mitchell P	2011	OPHTHALMOLOGY	118	615	The RESTORE Study Ranibizumab Monotherapy or Combined with Laser versus Laser Monotherapy for Diabetic Macular Edema	10.1016/j.ophtha.2011.01.031	RCT	1
25	369	Stulting RD	1999	OPHTHALMOLOGY	106	13	Complications of laser in situ keratomileusis for the correction of myopia	10.1016/S0161-6420(99)90000-3	Prospective, observational clinical study	0
25	266	Perezsantonja JJ	1997	J CATARACT REFR SURG	23	372	Laser in situ keratomileusis to correct high myopia	10.1016/S0886-3350(97)80182-4	Prospective study	0
24	519	Sekundo W	2011	BRIT J OPHTHALMOL	95	335	Small incision corneal refractive surgery using the small incision lenticule extraction (SMILE) procedure for the correction of myopia and myopic astigmatism: results of a 6 month prospective study	10.1136/bjo.2009.174284	Prospective, non-randomised clinical trial	5
24	473	Seiler T	1998	J REFRACT SURG	14	312	Iatrogenic keratectasia after laser in situ keratomileusis	10.3928/1081-597X-19980501-15	Prospective, observational clinical study	0
24	215	Hersh PS	1998	OPHTHALMOLOGY	105	1512	Photorefractive keratectomy versus laser in situ keratomileusis for moderate to high myopia - A randomized prospective study	10.1016/S0161-6420(98)98038-1	Randomized, prospective, multicenter clinical trial	0
22	242	Elman MJ	2015	OPHTHALMOLOGY	122	375	Intravitreal Ranibizumab for diabetic macular edema with prompt versus deferred laser treatment: 5-year randomized trial results	10.1016/j.ophtha.2014.08.047	RCT	1

Co-Occurring Author Keywords Networks

Analyzing the most cited keywords can indeed provide significant insight into research hotspots and trends. By extracting the timeline of the co-occurring authors' keyword network from 1990 to 2022 using CiteSpace (Figure 2A), we can see the pattern of each cluster over time. The term "diabetic macular edema" consistently appears with high frequency and the most bursts, marking it as the most active theme. "In situ keratomileusis" was active until 2010 but has received noticeably less attention since. "Optical coherence tomography", "phacoemulsification", and "intraocular pressure" started being less cited by researchers around 2005, while "dry eye disease" emerged as a new research hotspot.

When focusing on the 2017–2022 period (Figure 2B), we identified five primary clusters: "ranibizumab", "lasik", "macular degeneration", "glaucoma surgery", and "cataract surgery". Both co-occurring author keyword networks (1990–2022 and 2017–2022) exhibited significant silhouette scores (S>0.7) and acceptable modularity scores (Q>0.4), implying reasonable clustering quality.

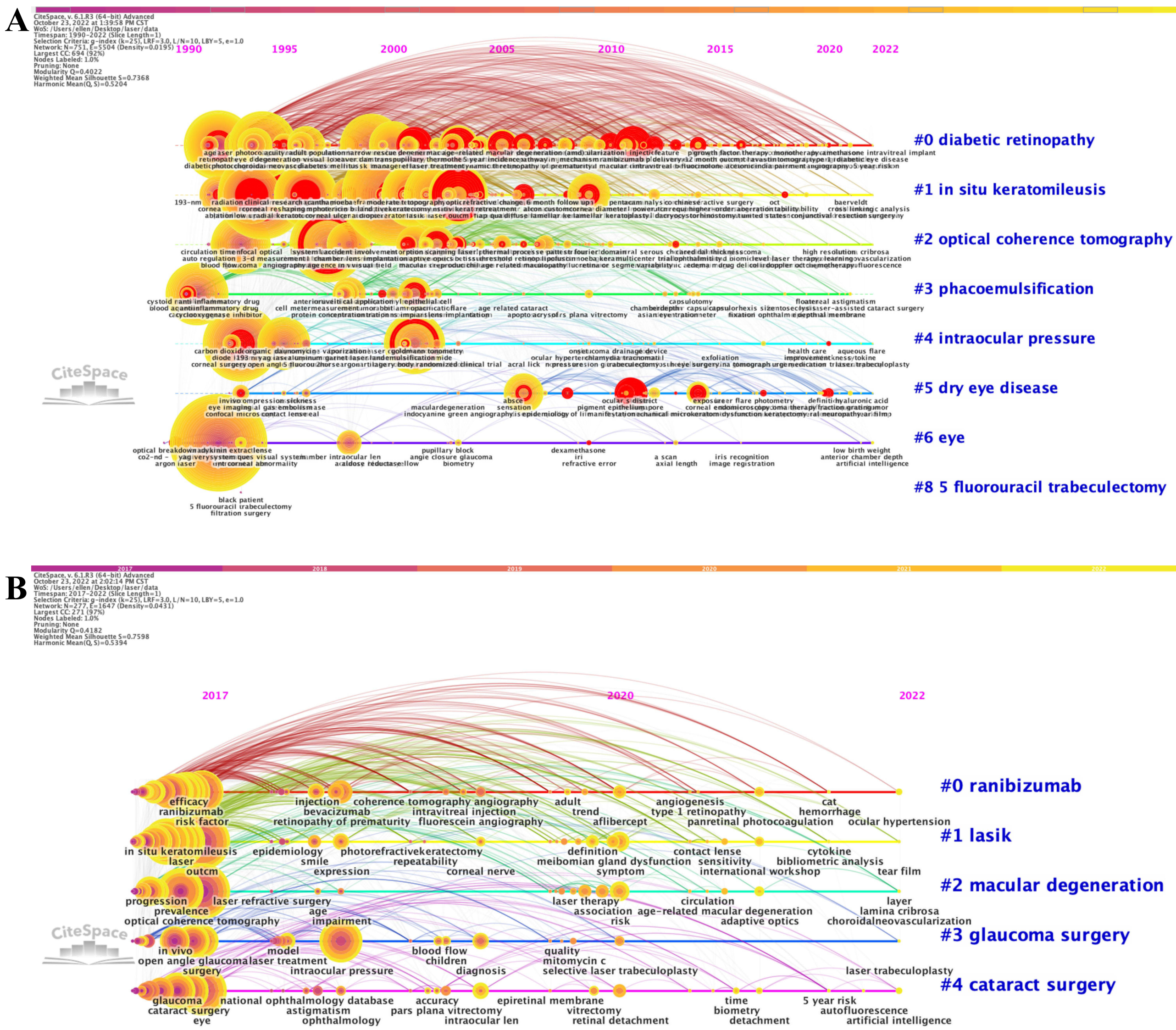

Figure 2 Timeline visualization of co-occurring author keywords networks ((**A**) 1990–2022 and (**B**) 2017–2022).

Notes: The nodes represent keywords, and the colors show the average year of publication for each node. The size of tree ring is proportional to the burstness of keyword co-occurrence. The co-occurrence network is weighted on total link strength across different keyword nodes and scored on the average publication years. The clusters are labeled in red at the far right of the timeline maps.

The burstness results revealed that the three most cited keywords with the strongest strength of citation bursts were "myopia" (1990, 24.69), "photorefractive keratectomy" (1990, 23.95), and "excimer laser" (1990, 14.54). Considering the 2017–2022 period, the keywords with the latest beginning of citation burst included "association", "bevacizumab", "retinal detachment", and "laser therapy". These keywords likely signal the latest trends in research (Supplementary Table 2).

We further extracted the overlay of visualization for the co-occurring author keywords networks based on the average publication years (1990–2022 period, Supplementary Figure 6). Some of the most cited keywords reflecting the latest research trends included "ocular hypertension", "meibomian gland dysfunction", "pediatric ophthalmology", and "dry eye disease". These terms likely point to future research directions in the field of laser ophthalmology.

Publication Outputs and Major Journals

The original dataset for our study included 3368 references. After adhering to our data filtering protocol, 677 references were excluded, leaving a total of 2691 references for analysis (Supplementary Figure 1). Looking at the annual scientific production trend, there was a low number of papers published annually before 1994. However, the output started to increase notably from 2000 onwards, reaching a peak in 2003 an average annual publication of 150. After a brief decline during 2004–2006, the annual output continued to increase until 2021. The average citations per year also showed an overall upward trend until 2016 (Supplementary Figure 7).

Regarding the sources of these references, the two journals with the most references from 1990 to 2022 were "Ophthalmology" and "Journal of Cataract and Refractive Surgery" (Supplementary Figure 8). However, in the period from 2017 to 2022, "Ophthalmology Retina" became the second most referenced journal, following "Ophthalmology". This shift reflects the evolution and expansion of research interests and focus on the field over time. The co-cited journal network, which provides an overview of the interconnectedness and interdependence of the various sources, along with the journals that published the most articles over the past 20 years, are presented in Supplementary Figure 9. These diagrams can be useful to identify key influencers and primary sources of information in the field.

Analysis of Cooperation Networks Across Countries and Institutions

Based on the analysis of the co-cited author's country network from 1990 to 2022 (Figure 3A and B), the USA consistently holds a central position with the highest degree of centrality (0.6), followed by Germany (0.19) and Italy (0.15). Supplementary Table 3 shows that the USA is the most frequently cited country (n = 1039), followed by Germany (n = 335), England (n = 242), the People's Republic of China (n = 163), and Japan (n = 144). When the timeframe is restricted to the last five years (2016–2021), China moves ahead of England, and India replaces Japan in the top five.

To further understand the collaborative network, we visualized the coauthor's institutions network for the 1990–2022 period with VOSviewer (Figure 3C). The top five institutions by citation count are Johns Hopkins University (n=83), Harvard University (n= 56), Medical University of Vienna (n = 44), Singapore National Eye Center (n = 44), and Moorfields Eye Hospital (n = 43). The top three institutions with the most recent and important strength of burst are Harvard Medical School, Johns Hopkins University, and Singapore National Eye Center (Supplementary Table 3).

The analysis of burstness reveals that India has the strongest citation burst strength of all times (11.64), with this burst occurring in the last five years. The burst detection analysis also shows that the University of Vienna has the strongest citation burst (14.42). The journal with the strongest citation burst strength is Ophthalmic Surgery, Lasers and Imaging Retina, both in the period from 1990 to 2022 and in the last five years (Supplementary Table 2).

Analysis of Co-Authorship Network

The analysis of citation bursts from 1990 to 2022 reveals that the top five co-authors with the strongest citation bursts were O Findl, David M Brown, Frank G Holz, David S Boyer, and Robert N Weinreb (Supplementary Table 2). We also constructed a co-authorship network with VOSviewer, which showed a similar network structure (Supplementary Figure 10).

We further examined citation patterns by investigating the author co-citation network for the years 2017 to 2022, which tells us "Who cites who" in our dataset. This author co-citation network displayed significant modularity, and the silhouette score indicated that the clusters were highly credible (Q=0.7491; S=0.9238) (Supplementary Figure 11). Eight

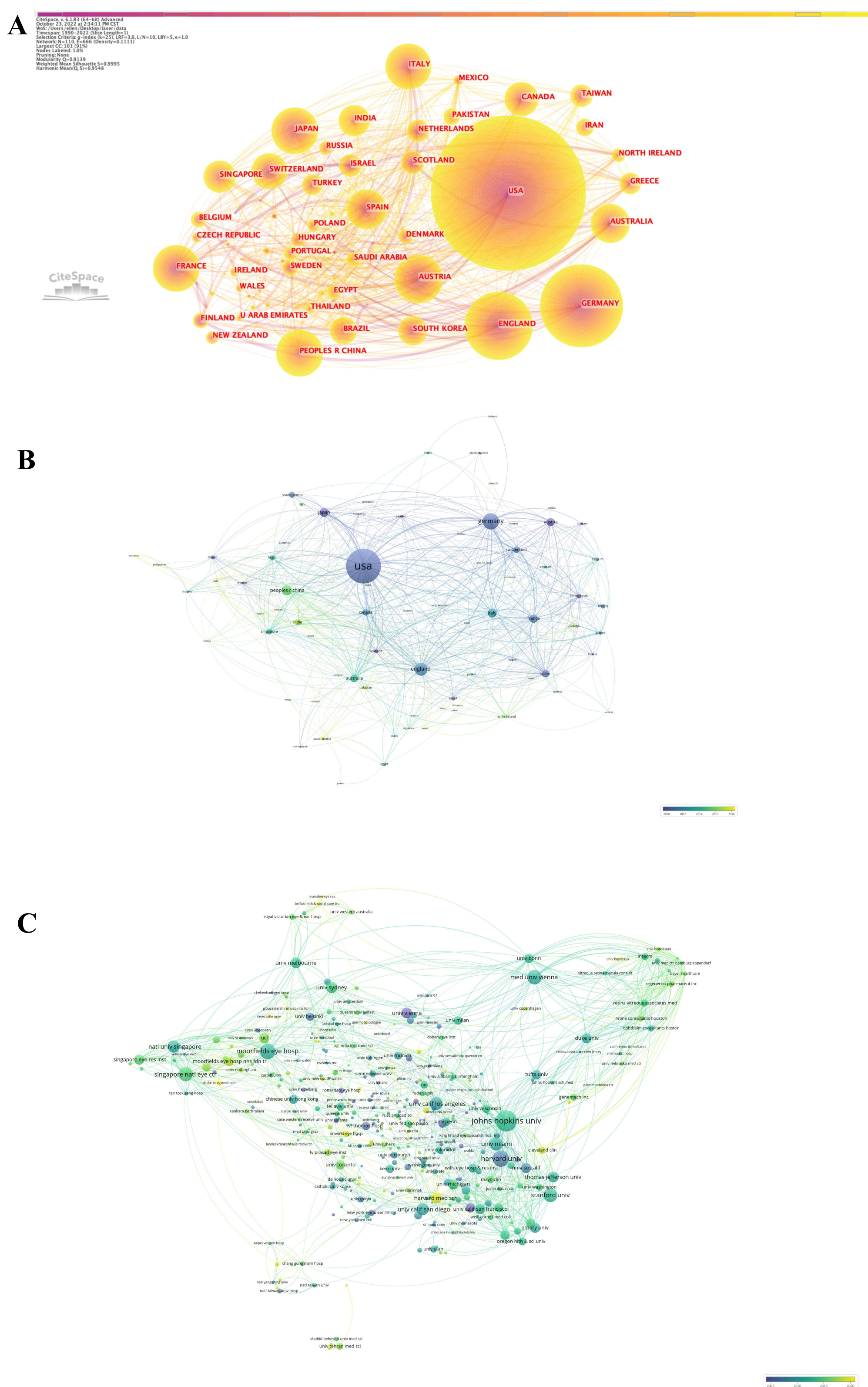

Figure 3 Network of the co-authors' countries obtained with CiteSpace (**A**), and Network of the co-authors' countries (**B**) and co-authors' institutions (**C**) for laser in ophthalmology from 1990 to 2022 obtained with VOSviewer.

distinct clusters were identified, with the most prominent recent cluster being cluster #0, which is labeled "diabetic macular edema" (Supplementary Table 4).

The top five authors with the strongest citation bursts from 1990 to 2022 were Seiler T, Hersh PS, Oshika T, Perez-Santonja JJ, and Knorz MC. However, in the most recent five years, the top five authors with the strongest citation bursts changed to Nagar M, Heijl A, Stein JD, Jabs DA, and Stapleton F (Supplementary Table 2).

Bibliographic Coupling Analysis of Countries, Institutions, Journals, References, and Authors

The present study performed the bibliographic coupling analysis to understand the current development and relationship between subjects, it is a useful addition to the author's co-cited analysis. In Figure 4, subjects having high similarity are placed closer to each other, and those that have low similarity are placed far from each other. The bubble size is in proportion to the total link strength. In the map of bibliographic coupling analysis, the USA is the country with the most total link strength, followed by Germany, England, Australia and England. As for institutions, the Johns Hopkins University, Singapore National Eye Center and Moorfields Eye Hospital are the top three institutions with the most collaborations with other organizations. The Ophthalmology and the Journal of Cataract and Refractive Surgery are the most crucial journals.

A report (Fercher et al) on the principles and applications of optical coherence tomography has the most average citations of any article. The next in rank are the RCTs of Nguyen et al[13] and Mitchell[15] for diabetic macular edema, and Leske's RCT for glaucoma management[23] (Supplementary Table 5).

Discussion

Summary of the Main Findings

This comprehensive scientometric study, analyzing 3368 references published from 1990 to 2022 and utilizing three different software packages (CiteSpace, VOSviewer, and Bibliometrix), presents a robust overview of the development and progression of laser technology in ophthalmology. This study not only traces the history of research in this field but also uncovers the influences shaping research networks. It provides researchers with valuable insights into the most influential papers, journals, and authors, as well as emerging research trends. The study identified three primary trends: the application of laser technology in refractive surgery, the use of lasers in treating various ocular diseases and innovative applications of existing technologies.

In terms of geographical contributions, the USA topped the list with the most total publications and citations, followed by Germany. However, over the last five years, England has seen a significant increase in publications and citation bursts, surpassing Germany. At the institutional level, Johns Hopkins University emerged as the most cited and productive institution overall. However, in the past five years, Harvard Medical School has taken the lead. The top five most productive and cited authors over the entire period were Seiler T, Hersh PS, Oshika T, Perez-Santonja JJ, and Knorz MC. In contrast, the most influential authors in the recent five years were Nagar M, Heijl A, Stein JD, Jabs DA, and Stapleton F.

The journal with the highest number of citations was "Ophthalmic Surgery, Lasers and Imaging Retina". The co-cited reference network (1990–2022) revealed coherent links between 18 different clusters and elucidated the evolution of research trends on laser use in ophthalmology, from changes in refractive surgery to changes in treatments for different diseases. This provides a valuable guide for future research directions and collaborations in this field.

Identification of Research Trends and Future of Evidence Synthesis

The obtained co-citation reference network presented 18 distinct clusters, illustrating the history of laser research in ophthalmology from 1990 to 2022 (Figure 1). Three major research trends were identified. The most significant trend was the evolution from the excimer laser to the femtosecond laser for refractive surgery. This evolution included clusters such as "photorefractive keratectomy", "rk", "light emitting diode", "aberrometry", "3d", and "anterior chamber". These clusters eventually merged with "biomedical optics" before moving on to "femtosecond laser" and "smile".

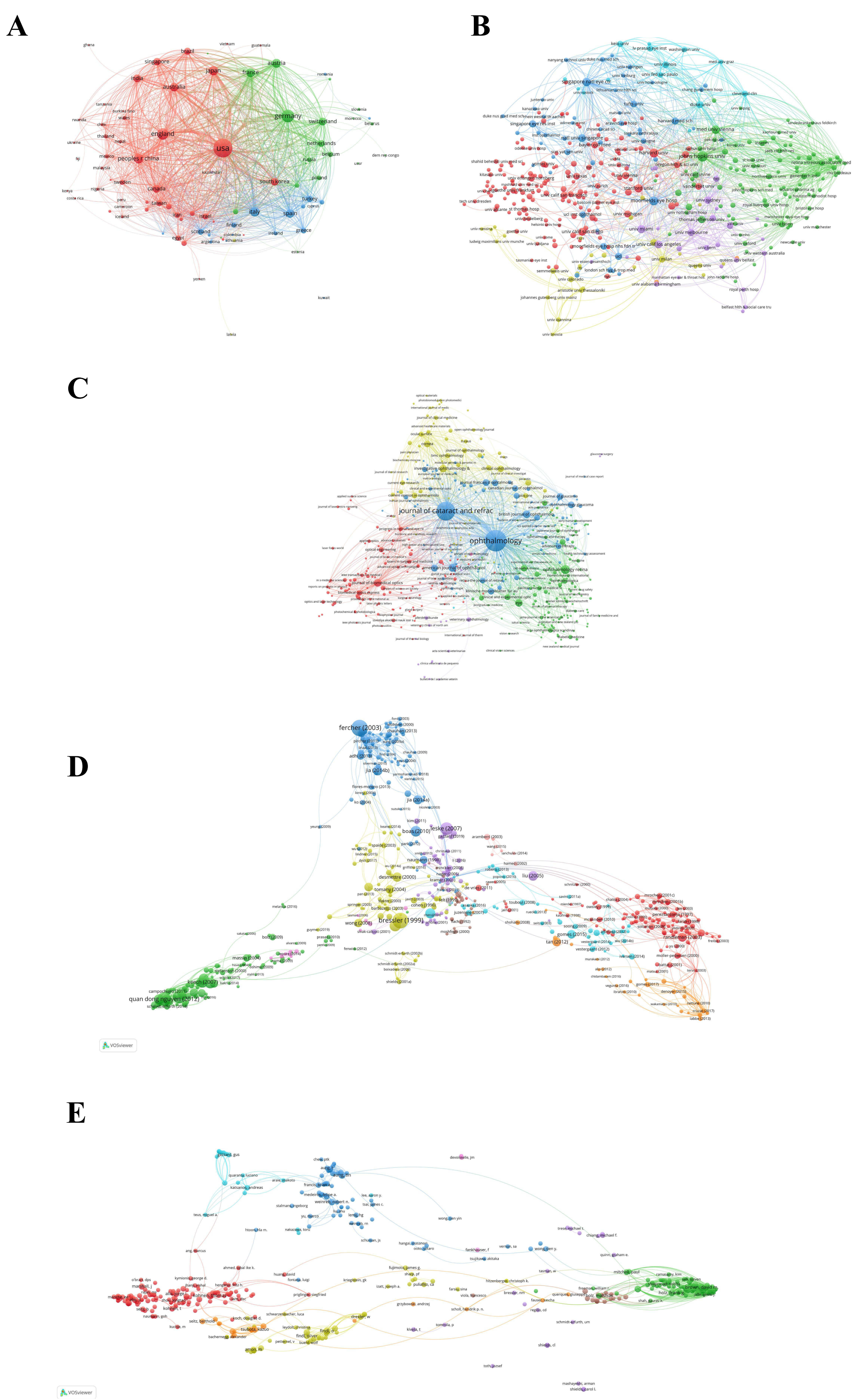

Figure 4 Map of bibliographic coupling analysis based on countries (**A**), institutions (**B**), journals (**C**), references (**D**), and authors (**E**) (weights on the total link strength).

Refractive errors, which result from a mismatch between the axial length of the eye and its optical power and lead to blurred vision, are a leading cause of reversible visual impairment worldwide.[24] Myopia, the most common refractive error, has garnered substantial scientific attention due to its high prevalence and the severe eye diseases associated with it.[24,25] Globally, corrective refractive surgery is one of the most frequently performed ocular procedures. Refractive surgery significantly impacts patients, as it not only improves vision and visual quality but also enhances work efficiency and quality of life. Refractive surgery has evolved through three generations. The first generation involved anterior radial keratotomy, performed without a laser. The development of excimer laser technology, which uses argon fluoride gases to emit ultraviolet laser pulses, gave rise to the second generation of refractive surgery.[26]

In 1983, research by Stephen Trokel, MD, of the Edward S. Harkness Eye Institute at Columbia University in New York, demonstrated the ability of the excimer laser to remove corneal tissue.[27] The study, published in the American Journal of Ophthalmology, used freshly enucleated cow eyes, and found that 1 joule/cm^2 could ablate corneal tissue to a depth of 1 μm, allowing for precise control over incision depth. In 1989, Marguerite B. McDonald, MD, reported a case of a patient who achieved clear and stable vision following excimer laser ablation, marking the first photorefractive keratectomy.[28] Following the FDA's approval of the excimer laser in 1991, I G Pallikaris and others developed a technique in the early 1990s that combined this technology with a modified microkeratome to create a central corneal flap.[29] Following this, an ArF excimer laser was used to produce 3-mm-diameter circular ablations on the central part of the exposed stromal bed. This technique, which Pallikaris dubbed "LASIK", has since become a widely used refractive technique worldwide. However, LASIK carries risks, including flap inflammation and traumatic flap dislocation. In contrast, surface ablation, which does not create a flap, involves the removal of corneal stroma with an excimer laser after the corneal epithelium has been removed. The corneal epithelium can be removed in one of three ways: with 20% alcohol (Laser-assisted Subepithelial Keratectomy, LASEK[30]), a motorized brush (Photo Refractive Keratectomy, PRK[28]), or directly by excimer laser ablation (Transepithelial Photo Refractive Keratectomy, T-PRK[31]). In 2003, a study by Keith P Thompson and others compared an aberrometry-guided laser treatment (InterWave LASIK) with standard LASIK treatment based on the manifest refraction and found that the former resulted in superior quality mesopic vision.[32]

Biomedical photonics, which amalgamates research in physics, optics, and electrical engineering, is one of the fastest-growing fields in life sciences, particularly for medical and biological applications.[33] In 1998, the first lamellar refractive surgical procedure was conducted on fresh porcine and primate cadaver eyes using a solid-state femtosecond laser,[34] marking the onset of the third-generation femtosecond era. In 2001, a corneal flap was initially created using a femtosecond laser for IntraLASIK surgery.[35] Following the FDA's approval in 2010, femtosecond lasers were cleared for clinical use, leading to the emergence of new surgical methods, including FS-LASIK, and more recently, SMILE, which is currently the most common surgery.[36] In 2010, SMILE was introduced to China, and Professor Zhou of Eye & ENT Hospital, Fudan University performed the first surgery.

The advancement of refractive surgery technology has progressively enhanced the minimally invasive, precise, and safe nature of the procedure, thereby providing patients with an improved experience. Simultaneously, researchers are increasingly focusing on safety evaluations related to refractive surgery, including postoperative dry eye, corneal ectasia resulting from biomechanical changes, corneal infection, visual quality concerns, and other issues. However, cataract surgeons primarily emphasize the impact of a patient's history with refractive surgery on cataract surgical outcomes.[37] For instance, Professor Cione et al investigated and proposed multi-formula approach for calculating intraocular lens power after myopic laser-refractive-surgery.[38,39]

The second trend pertains to the use of lasers for different diseases, with clusters including "age-related macular degeneration", "biomedical optics", "diabetic macular edema", "dry eye disease", "glaucoma", and "diabetic retinopathy". In 1993, K. Bailey Freund, MD, and colleagues[40] studied a series of patients with neovascular age-related macular degeneration (AMD) to determine eligibility for laser photocoagulation treatment. Today, however, laser photocoagulation for AMD has largely been replaced by new anti-VEGF agents.[41] A randomized controlled trial by Fong et al[42] compared two laser photocoagulation techniques for treating diabetic macular edema (DME): the modified Early Treatment Diabetic Retinopathy Study (ETDRS) direct/grid photocoagulation technique and a potentially milder mild macular grid (MMG) laser. The safety and effectiveness of other lasers, such as the subthreshold diode micropulse laser photocoagulation (SDM)[43] and the yellow subthreshold micropulse laser (YSML),[44,45] have also been studied. Nevertheless, the risks associated with photocoagulation, including choroidal neovascularization, permanent photoreceptors loss, laser scars, and subretinal fibrosis, are significant.[46–48] Consequently, intravitreal anti-VEGF injections have become a standard treatment regimen for DME.[49]

While laser treatments for AMD and DME seem to be progressively replaced by drug therapies, the treatments for dry eye disease (DED) and glaucoma are increasingly employing lasers. Various treatments for DED, which addresses tear insufficiency and lid abnormalities, were reviewed in the "TFOS DEWS II Management and Therapy Report".[50] These treatments include anti-inflammatory medications, surgical approaches, dietary modifications, environmental considerations, and complementary therapies. Recently, studies have begun to evaluate the effect of optimal pulse light technology (OPT) intense pulsed light (IPL) in treating dry eye. The results indicate that IPL treatment could improve the quality of the tear film lipid layer, reduce clinical signs and symptoms of DED, and thus decrease the frequency of artificial tear use.[51]

There are three primary strategies for treating glaucoma: laser treatment, incisional surgery, and medication.[52] In 1979, Wise JB first introduced argon laser trabeculoplasty (ALT),[53] a technique that effectively lowers intraocular pressure (IOP). Two decades later, selective laser trabeculoplasty (SLT), introduced by Latina MA and Park C.[54] became the most popular laser treatment for primary open-angle glaucoma (POAG). A Phase II clinical study in 2008[55] reported a mean IOP reduction following treatment with micropulse diode laser trabeculoplasty (MDLT). For patients with refractory glaucoma, other options include endoscopic cyclophotocoagulation (ECP)[56] and transscleral cyclophotocoagulation (TCP). Laser iridotomy (LPI) has been used to treat nearly all types of narrow-angle glaucoma.[57] Assisted Nd: YAG puncture following deep sclerotomy can transform non-penetrating surgery into full-thickness surgery, thereby lowering IOP.[58] Excimer laser trabeculotomy (ELT) has demonstrated minimal thermal effects on the trabecular meshwork.

The final trend focuses on the use of femtosecond technology in cataract surgery, according to the co-citation reference network for the past five years (2017–2022). Femtosecond laser-assisted cataract surgery (FLACS) represents a paradigm shift in cataract surgery. However, a meta-analysis of 14,567 eyes[59] found no statistically significant differences between FLACS and manual cataract surgery (MCS) in terms of important visual and refractive outcomes and overall complications. Still, FLACS showed superiority over MCS in corneal wound creation, astigmatic keratotomy, capsulotomy, and reduction in ultrasound energy.[60] Given the recent advancements, it is anticipated that the use of lasers in ophthalmology will continue to expand, potentially leading to the development of even more novel technologies.

Relevance of Bibliometrics Studies for Evidence Synthesis

The collaboration network encompasses the co-authorship network of co-authors' countries and institutions. When combined with the clusters from the co-citation reference network, researchers can visualize the impact of research teams in generating scientific knowledge and assess potential candidates for research collaboration. The use of bibliometric analyses provides multiple benefits for researchers.[61] For instance, systematic reviews of published corpora can be extracted and visualized, thereby synthesizing the main research trends derived from selected search terms. Additionally, networks of co-occurring author keywords and keyword bursts can reveal the keywords most relevant to a specific research trend. This aids in selecting a list of keywords for database search.[62]

The evolution of research trends, along with the latest areas of research interest, productivity, and their trends, are identified through significant intellectual turning-point papers. These often represent the core papers of a cluster and are essential to understanding the evolution of research trends. They can also inform the introduction and rationale for writing systematic reviews.[63] Moreover, journal analysis and co-citation journal analysis can provide crucial information for researchers in selecting the most suitable journal for paper submission. Lastly, the analysis of countries and institutions may lead to the funding of critical projects and foster international institution-to-institution cooperation.[64]

Strengths and Limitations

Based on the literature review, this study is the first bibliometric analysis on the use of lasers in ophthalmology. Unlike narrative reviews, bibliometric analysis can provide a comprehensive guide on the history and emerging trends of research for clinicians and scholars. Furthermore, it can outline potential areas for future trials addressing clinically relevant questions that existing studies may not have adequately explored. This work can also assist in identifying leading authors and journals in the field of laser applications in ophthalmology. It can guide early-career researchers in identifying mentors and institutions and help them seek out stakeholders, policymakers, and funding institutions within the clinical and scientific community for the direction of laser applications in ophthalmology.

A significant limitation of bibliometric studies is the use of citation-related indicators, as these can introduce various biases, especially citation biases. Factors such as authorship, journal influence, and self-citation have been found to be crucial determinants of citation.[65] Other potential biases include novelty bias, outcome reporting bias, location bias, and publication bias. Publication bias is a pervasive problem that can significantly skew research result estimates.[66] Another limitation is that the data collected was only available from the Web of Science Core Collection (WOSCC). Most databases, such as PubMed, Embase, and the Cochrane Systematic Review databases, do not provide full-text and citation analysis, leading to a potentially incomplete retrieval of publications. However, WOSCC is the most suitable database for scientometric research. Future software developments may enable the simultaneous use of different databases and reliable automatic removal of duplicates.

Conclusion

This bibliometric study offers historical insights and perspectives on the global application of lasers in ophthalmology. The number of published papers has experienced significant growth over the past 32 years, with a surge in 1999 and over 100 papers published annually since 2011. The report identifies the most influential countries, institutions, and authors, as well as research hotspots and recent trends. These trends include technological innovations in corneal laser surgery in refractive surgery, shifts in the application weight of lasers in different ophthalmic diseases, and fresh explorations and applications of existing laser technologies in eye diseases. The United States and Europe are the primary publishing countries, and Asian countries and institutions could benefit from increased collaboration with them. Our study delivers useful information for researchers to understand the development of laser applications in eye diseases and is poised to provide valuable insights for researchers, grant applicants, funding agencies, and policymakers.

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