• Bibliometric Research •

Bibliometric and visual analysis of scleral contact lenses: global characteristics and research trends from 1976 to 2023

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Abstract

● **AIM:** To gain insight into the future research directions in scleral contact lenses (SCLs) through a comprehensive bibliometrics study.

● **METHODS:** The publications related to SCLs were screened from the Web of Science Core Collection (WOSCC) database. All bibliographic information was extracted and used to conduct a performance analysis. CiteSpace and VOSviewer were employed to visualize annual publication counts, journals, authors, countries, institutions, collaboration networks, keywords, and references.

● **RESULTS:** A total of 498 articles were included in our analysis and the number of publications about SCLs showed a significant yearly increase. These publications predominantly emanated from 523 institutions across 38 countries, with the United States and Australia leading in frequency. Totally 1361 authors were identified, among whom Vincent J. Stephen exhibited the highest number of publications, while Jacobs S. Deborah received the most citations. Notably, the journal *Contact Lens & Anterior Eye* emerged as the primary publisher of studies, and it also boasted the highest citation rate. “Fluid-ventilated, gas-permeable scleral contact lens is an effective option for managing severe ocular surface disease and many corneal disorders that would otherwise require penetrating keratoplasty” was the most cited paper published in eye & contact lens in 2005. The most prevalent keywords encompassed “keratoconus”, “scleral contact lenses”, “management”, “contact lenses”, “scleral contact lens”, “ocular surface disease”, “dry eye”, and “contact lens”.

● **CONCLUSION:** Although SCLs have demonstrated significant potential in ophthalmological care, the results offer valuable insights pertinent to future research directions and clinical practice. Greater emphasis should be placed on developing enhancements in design, materials, and fitting technique, as well as on reducing the complications associated with SCLs.

● **KEYWORDS:** scleral contact lenses; bibliometric analysis; visual analysis

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INTRODUCTION

Scleral contact lenses (SCLs) are rigid, gas-permeable, wide-diameter contact lenses that rest on the sclera, vault over the whole cornea, creating a fluid reservoir between the ocular surface and posterior surfaces of the lens. The modern SCLs has evolved from the first device resembling SCLs in 1887[1]. With the advent of high oxygen permeability (Dk) of rigid contact lens materials, the complications that were seen with older generation SCLs related to hypoxia have reduced[2]. SCLs could offer the wearers a comfortable experience of correcting ocular surface irregularities, allowing for the treatment of various ocular surface diseases, and served as nonsurgical alternatives in severe cases who need for keratoplasty[3]. However, as with any new contact lens modality, the modern SCLs brings with it a new set of issues. SCL is generally safe, but ophthalmologists and optometrists must be aware of SCL related complications that may be sight threatening[4]. Therefore, it is imperative identify the indications, complications, and clinical outcomes of SCLs.

Bibliometric analysis was first proposed in 1923 by Hall and Hulme[5]. It is a quantitative research method based on publications, citations, and textual data, used to describe and analyze the dynamics and progress of a discipline or research field. The results of bibliometric studies encompass not only performance analysis but also visualized maps. This method provides a broad overview of a knowledge domain and can help identify research questions that researchers may seek

to answer, as well as the methods authors have developed to achieve their goals[6-9].

Several bibliometric analyses of the SCLs" literature were undertaken previously[10-11]. However, the data were retrieved from the Scopus database. No bibliometric studies on SCLs were done using the Web of Science (WOS) so far. To fill this gap, this bibliometric analysis constructs a global map of scientific publications on SCLs.

MATERIALS AND METHODS

Data Source WOS stands as one of the foremost academic database sources, encompassing a repository of over 12 000 influential journals. It is widely acknowledged as the most comprehensive and dependable database for conducting bibliometric analyses[12-13]. We collected data from WOSCC until September 20, 2023, and the download process was completed within a single day. The search strategy was configured as follows: TS= ("scleral lens" OR "scleral lenses" OR "scleral contact lenses" OR "scleral contact lens"), with a filter for articles and reviews published in English only. This search yielded a total of 510 pieces of literature. All retrieved studies underwent rigorous evaluation by two ophthalmologists independently to ensure their relevance to the research topics. In cases where the two reviewers had conflicting assessments, a third reviewer independently assessed the paper to reach a consensus. As a result, 12 irrelevant articles were excluded, leaving 498 articles for the final analysis. The detailed procedure for literature screening was presented in Figure 1. Relevant articles were exported and saved in plain text format (including full records and cited references) for subsequent analyses.

Data Analysis and Visualization All valid data collected in WOSCC was imported to CiteSpace (version 6.2.R4)[14] and VOSviewer (version 6.2.R4)[15] software for visual analysis. Both software tools offer distinct advantages and can effectively complement each other. CiteSpace employs a data standardization method rooted in set theory to assess the similarity of knowledge units. This similarity algorithm is applied to generate the Timezone view and Timeline view within specific time slices. Consequently, this approach provides a clear representation of the evolution of knowledge and the historical context of literature clusters over time. It enables a comprehensive understanding of the field"s development process and trends[14,16]. VOSviewer utilizes a data standardization method grounded in probability theory and offers a range of visual representations in various domains such as keywords, co-institutions, and co-authors. It provides Network Visualization, Overlay Visualization, and Density Visualization, distinguished by their user-friendly and visually appealing features, making them suitable for creating simple yet aesthetically pleasing images[15-17]. We employed CiteSpace

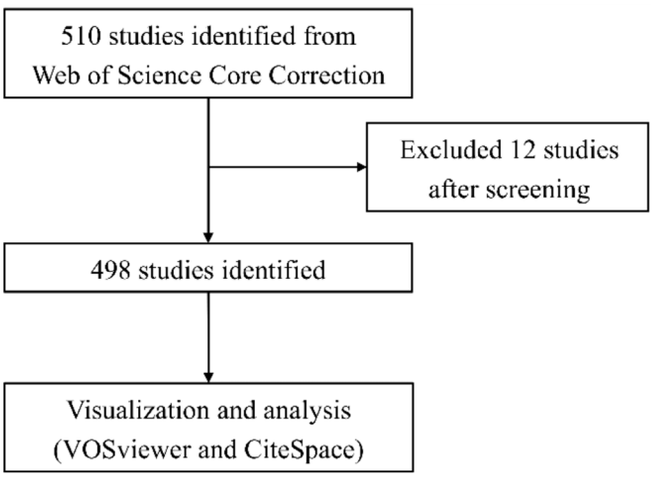

Figure 1 Flowchart of literature selection.

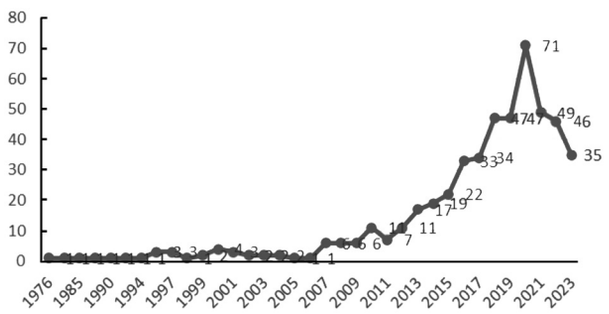

Figure 2 Number of annual articles on SCLs by years SCLs: Scleral contact lenses.

to examine the trend in the number of articles published each year and utilized VOSviewer to analyze the distribution of countries/regions and institutions, author contributions, core journals, citation frequencies, and co-occurring keywords.

RESULTS

Publication Output and Growth Trends As illustrated in Figure 2, the overall trend in annual publications pertaining to SCLs demonstrates a consistent upward trajectory. This trend commenced with a single publication in 1976 and escalated to seventy-one in 2020, subsequently plateauing at thirty-five by September 20, 2023. Activity in this field remained relatively subdued from the 1970s through the early 2000s, with fewer than five articles annually. However, research endeavors gained momentum in the late 2000s. Consequently, there was a noteworthy surge in the 2010s, culminating in 71 publications in 2020. There was a modest dip in 2021, with 49 articles, followed by a slight decrease to 46 articles in 2022. The evolving trend in the number of publications associated with SCLs delineates a dynamic research landscape characterized by fluctuating levels of activity and an escalating interest in the field over the past few decades.

SCLs are subject of novel international interest, garnering research contributions from 38 countries/regions. The United States stands out prominently, leading in national research output with 231 publications and 4946 citations. Australia

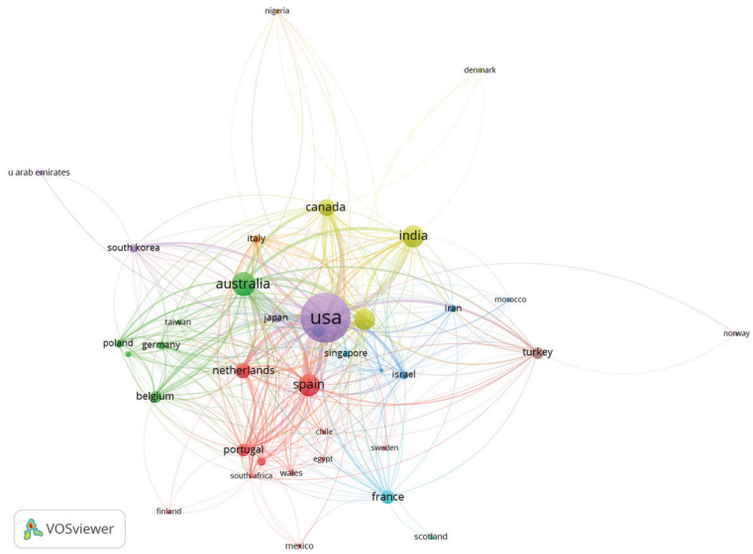

Figure 3 The distribution and interconnection of literature pertaining to SCLs across various countries/regions SCLs: Scleral contact lenses.

Table 1 Top 10 institutions publishing papers on SCLs

Rank	Affiliations	Country	Articles, *n*	Citation, *n*
1	Mayo Clinic	United States	34	599
2	The University of Houston	United States	30	102
3	The Queensland University of Technology	Australia	29	552
4	The Ohio State University	United States	21	218
5	The University of Illinois	United States	21	264
6	The Boston Foundation for Sight	United States	21	850
7	The L V Prasad Eye Institute	United States	21	379
8	Illinois College of Optometry	United States	17	160
9	Harvard University	United States	16	714
10	The University of Minho	Portugal	15	321

SCLs: Scleral contact lenses.

follows with 52 publications and 882 citations, while Japan and Spain rank third with 45 publications. England holds the fifth position with 42 publications, accompanied by a remarkable 1336 citations. Figure 3 illustrates the distribution of publications. Each node in the figure represents a country, with the node"s size indicating the country's publication output. The curved lines between the nodes indicate cooperation between countries, with wider lines denoting closer collaboration. Most countries have demonstrated active cooperation, including the USA, Spain, India, England, Canada, Netherlands, Portugal, and France.

In total, 523 institutions have made significant contributions to SCLs research. Table 1 displayed the top 10 most productive institutions in this field. Leading in productivity is the Mayo Clinic, with 34 publications and 599 citations. The University of Houston closely follows with 30 publications and 505 citations, and the Queensland University of Technology with 29 publications and 552 citations. Notably, the Boston Foundation for Sight ranks fourth with 21 publications and an impressive 850 citations. Harvard University, with 16 publications, holds the ninth position with an astonishing 714 citations. Furthermore, 46 institutions have met the criteria of publishing a minimum of 5 articles about SCLs.

This current search yielded a total of 498 articles on SCLs, published across 80 different journals. Figure 4 displayed the key journals that made the most significant contributions to these publications. *Contact Lens & Anterior Eye* leads as the most prolific journal, with 111 publications, followed by *Eye & Contact Lens - Science and Clinical Practice* with 99 publications, and *Optometry and Vision Science* with 63 publications. *Cornea* ranks fourth with 29 publications, boasting a high citation count of 1056.

A total of 1361 authors contributed to the 498 publications, resulting in an average of approximately 3 authors per article. Vincent J. Stephen ranks for first place with 33 publications and 588 citations, followed by Deborah S. Jacobs with 28 publications and 757 citations, and Muriel M. Schornack with 27 publications and 551 citations. Citation analysis of authors reveals that out of the 1361 authors, 60 had published at least five papers. The largest set of associated authors consisted

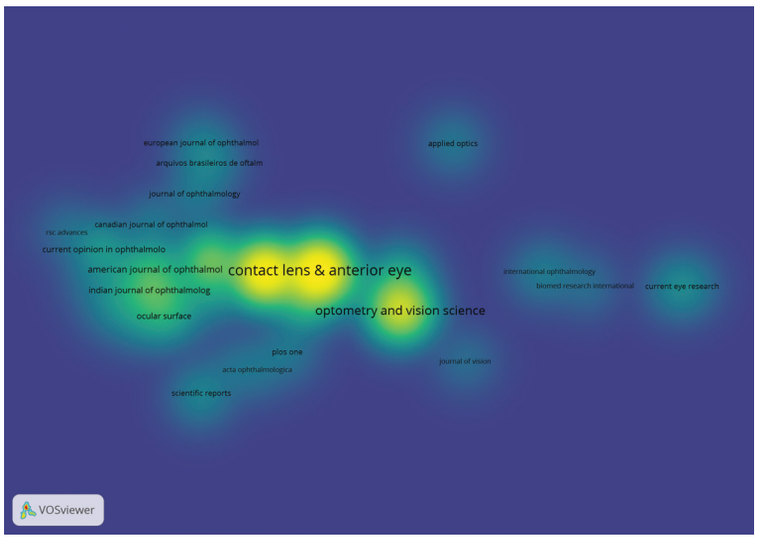

Figure 4 The key journals that have made substantial contributions to this field.

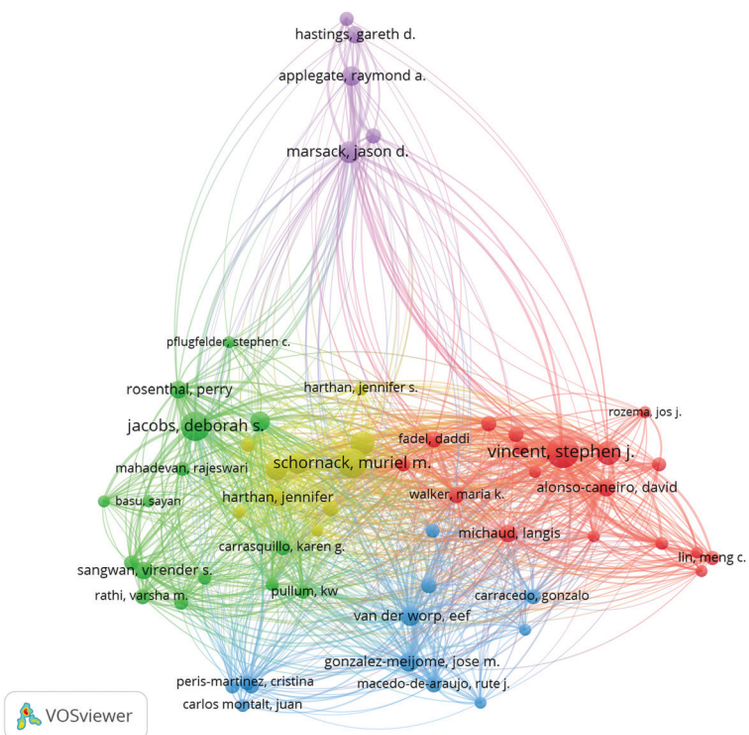

Figure 5 The network of most productive authors who contributed to scleral contact lenses.

of 60 individuals distributed across five clusters, as shown in Figure 5.

Reference Co-Citation Analysis We delved deeper into the knowledge base concerning SCLs, uncovering 498 pertinent articles that collectively garnered 10 857 citations—an average of 21.80 references per article. Table 2 showcases the top 10 highly cited papers. The most cited paper, titled "Fluid-ventilated, gas-permeable scleral contact lens is an effective option for managing severe ocular surface disease and many corneal disorders that would otherwise require penetrating keratoplasty" was published in *Eye & Contact Lens* in 2005[18], with Rosenthal Perry as the corresponding author. We then selected the top 100 articles, each cited at least 20 times, and represented them in a visualization network map using VOSviewer for co-cited references in SCLs. Figure 6 delineated three main clusters, distinguished by various colors.

Co-Occurrence Analysis of the Top 97 Keywords Keywords serve as representative markers for the research themes and core content of literature. Through keyword co-occurrence analysis, we gain valuable insights into the distribution and development of different research hotspots within a specific field. We utilized VOSviewer to extract and cluster the top 97 keywords. Figure 7 presented a visual network diagram illustrating the co-occurrence relationships among these key terms. The size of nodes indicates the frequency of keyword occurrence, while the distance between two nodes signifies

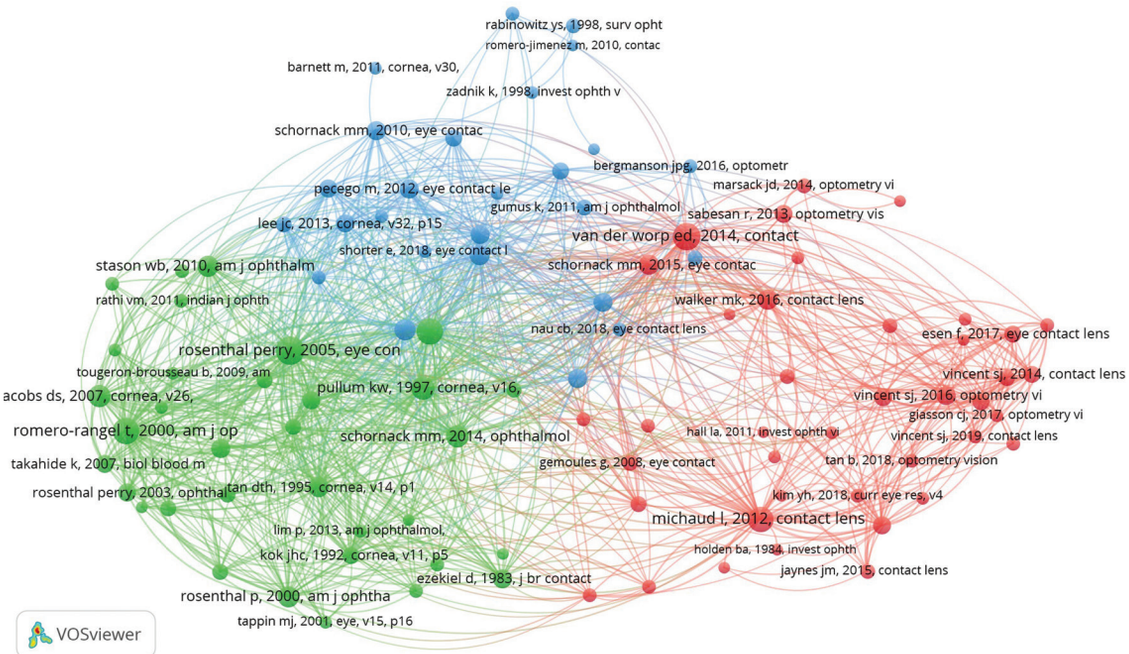

Figure 6 The co-cited references in scleral contact lenses.

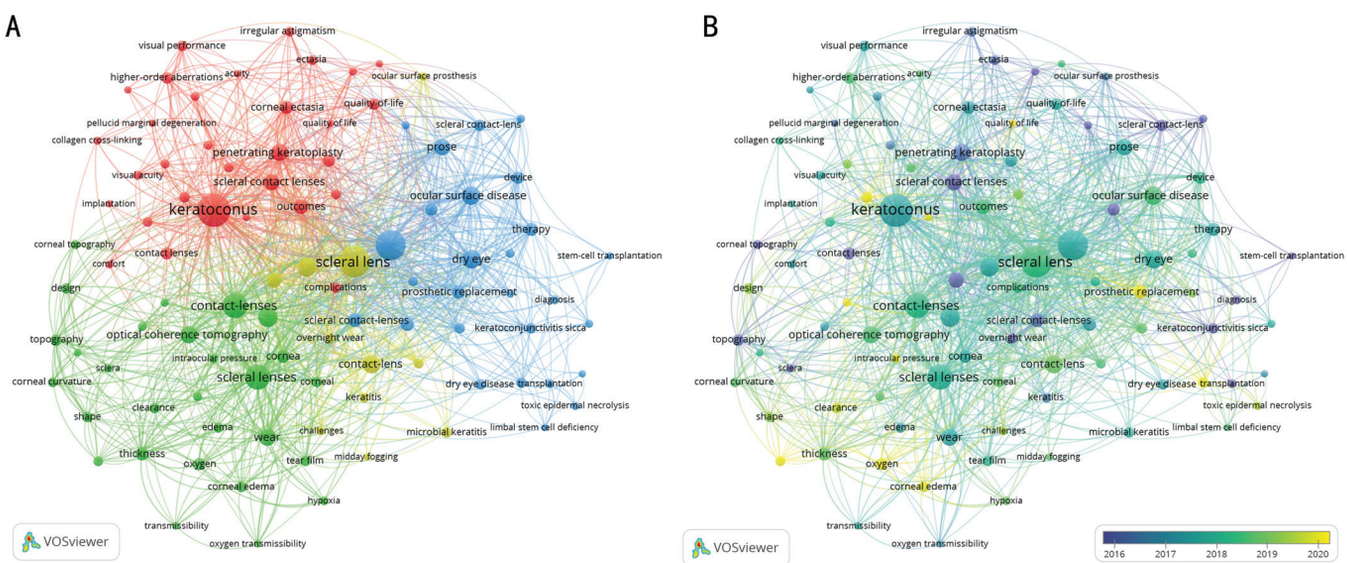

Figure 7 The co-occurrence network of the top 97 keywords in SCLs research SCLs: Scleral contact lenses.

Table 2 Top 10 high cited articles in SCLs research

Rank	Year	Author name	Title	Journal	Citation, *n*
1	2005	Perry *et al*	Fluid-ventilated, gas-permeable scleral contact lens is an effective option for managing severe ocular surface disease and many corneal disorders that would otherwise require penetrating keratoplasty	*Eye & Contact Lens*	111
2	2014	Eef *et al*	Modern scleral contact lenses A review	*Contact Lens & Anterior Eye*	102
3	2007	Tatiana *et al*	Gas-permeable scleral contact lens therapy in ocular surface disease	*American Journal of Ophthalmology*	100
4	2004	Kenneth *et al*	Scleral contact lenses: the expanding role	*Cornea*	98
5	2012	Langis *et al*	Predicting estimates of oxygen transmissibility for scleral lenses	*Contact Lens & Anterior Eye*	88
6	1997	Kenneth *et al*	A study of 530 patients referred for rigid gas permeable scleral contact lens assessment	*Cornea*	74
7	2007	Deborah *et al*	Boston scleral lens prosthetic device for treatment of severe dry eye in chronic graft-versus-host disease	*Cornea*	68
8	2014	Muriel *et al*	Scleral lenses in the management of ocular surface disease	*Ophthalmology*	67
9	2000	Perry *et al*	Treatment of persistent corneal epithelial defect with extended wear of a fluid-ventilated gas-permeable scleral contact lens	*American Journal of Ophthalmology*	65
10	2003	Ori *et al*	Scleral contact lenses may help where other modalities fail	*Cornea*	64

SCLs: Scleral contact lenses.

the strength of their association. This visual representation highlights the most significant keywords, with the top 10 being: "keratoconus" (142), "scleral lens" (128), "management" (116), "contact lenses" (84), "scleral lenses" (83), "scleral contact lens" (48), "contact lens" (47), "ocular surface disease" (45), "dry eye" (45), and "contact-lens" (42).

Keywords with closer distances were grouped into the same cluster, providing a rough reflection of the main topics in SCLs research. VOSviewer automatically organized similar keywords into four distinct clusters, represented by different colors: Cluster 1 (Red) primarily focuses on the indications and clinical outcomes related to SCLs. Keywords such as "keratoconus", "scleral contact lenses", "penetrating keratoplasty", "outcome", "cornea ectasia", "higher-order aberrations", "quality-of-life", and "visual performance" are prominent. Cluster 2 (Green) concentrates on the fitting technique and potential complications of SCLs. Main keywords include "contact-lenses", "optical coherence tomography", "wear", "thickness", "oxygen, "cornea edema" "tear film", "clearance", and "intraocular pressure". Cluster 3 (Blue) centers on novel materials of SCLs and expanding indications, primarily involving "management", "ocular surface disease", "dry eye", "prose", "therapy", and "device". Cluster 4 (Yellow) features keywords such as "scleral lens", "contact lens", "medical applications", and "overnight wear".

DISCUSSION

This bibliometric analysis examined the development of SCLs research over the past 40y. The number of publications about SCLs has shown an enormous growth trend over the past few decades, particularly since 2010. The increased research activity in this field may be attributed to the emergence of advanced anterior surface analysis systems, such as optical coherence tomography (OCT), along with new computerized lathing methods. Additionally, the introduction of new high Dk materials has made scleral lenses more predictable and safer[19], leading to an increase in research funding. It's noteworthy that the majority of articles were published in English, a trend in line with the predominantly English-language content found in the WOSCC database and the widespread use of English as the primary academic language worldwide.

In this bibliometric analysis, a majority of the pertinent articles were authored by corresponding scholars from various countries, including the USA, England, and Australia. Academic prowess is often closely correlated with the economic standing of a nation. Moreover, government expenditure on healthcare serves as a pivotal indicator of medical research productivity. The USA, for instance, leads in healthcare expenditure, surpassing 4.2 trillion U.S. dollars in 2021, with individual healthcare spending averaging 10 784 U.S. dollars per resident. This significant investment in healthcare may partially account for the exceptionally high volume of publications originating from the USA[20-21]. Noteworthy are the accomplishments of Indian scholars in the realm of SCLs research, amassing 45 publications and 615 citations. This is likely attributable to India well-developed eye care system, despite its status as a developing nation[22-24].

Hotspots denote specific scientific themes within a defined research domain over a particular period, constituting a pivotal element of bibliometric analysis. Citation analysis stands as a valuable method for evaluating the scholarly influence of publications[25]. Among the ten most frequently cited articles identified in this study, the predominant emphasis has been on novel materials and indications for SCLs. These areas also represent current focal points in recent research endeavors. Additionally, there is a burgeoning scholarly interest in complications and fitting technique pertaining to SCLs.

Keywords serve as crucial indicators in scientific research, encapsulating the essence of pertinent papers. Keyword co-occurrence analysis serves to illustrate the interconnectivity and prevalence of research themes within scientific domains[26]. Among the frequently cited keywords, in addition to "scleral lens", other commonly utilized terms revolved around indications of SCLs. Moreover, keywords pertaining to complications, innovative materials, and diagnostic tools surfaced prominently. Furthermore, "outcomes", "visual performance", and "quality-of-life" were frequently cited, signifying an increasing emphasis on the clinical effects of SCLs[27].

Cluster analysis was conducted using these keywords, leading to the formation of four distinct colored clusters. Subsequently, employing a timeline viewer analysis of these clusters, we identified research hotspots and development frontiers in the field of SCLs. The key findings are outlined below: SCLs constitute an essential tool in ophthalmic and optometric practices, particularly in specialized clinics focused on corneal conditions, refractive correction, and ocular surface diseases[28]. At its inception, SCLs were primarily designed to correct refractive errors, especially irregular astigmatism. Currently, the indications for SCLs include improving visual acuity in patients with irregular corneas, encompassing conditions encountered in corneal ectasias, post-trauma, and following anterior segment surgeries. The advancement of enhanced SCLs technology has expanded its range of applications. It is now proving effective in treating various ocular surface diseases, particularly in cases where conventional therapies, such as those for Stevens-Johnson syndrome and exposure keratopathy, have shown limited success. Additionally, SCLs are employed for the correction of simple refractive errors and for cosmetic purposes[3-4,29-31].

Over the past decade, numerous contact lens manufacturers have expanded their product offerings to include scleral lens

designs[32-33]. Thanks to advancements in precision lathing techniques, intricate lenses can now be produced with a high degree of reproducibility. Additionally, preformed scleral lens diagnostic fitting sets, crafted from highly oxygen-permeable materials, have streamlined in-office fitting procedures for practitioners. Moreover, practitioners can still employ impression techniques to accurately capture abnormal ocular surfaces. Furthermore, a range of customizations are available to practitioners, including back surface haptic Toric, quadrant-specific, and multifocal designs[34-35].

Advances in ophthalmic instrumentation have not only simplified the scleral lens fitting process, but have also deepened our understanding of peripheral corneal shape, the limbal junction, and scleral morphology. Modern rigid contact lens practitioners now consider corneal topographers with features like composite map pasting and simulated post-lens tear layers as essential tools. Additionally, cornea-scleral topographers have emerged to provide reliable estimates of scleral curvature and sagittal depth at the anticipated landing zone of scleral lenses. One of the most significant technological breakthroughs contributing to the current and future surge in scleral lens prescribing is the introduction of ocular OCT[36-38]. OCT imaging not only enables a non-invasive *in vivo* examination of the relationship between a scleral lens and the cornea (including central and limbal clearance), but also sheds light on the impact of lens wear on the conjunctiva and sclera. Furthermore, it has enriched our understanding of the anatomy and physiological variations in the conjunctiva and sclera, which are crucial aspects in scleral contact lens practice and research[34,39].

While the utilization of SCLs is generally safe, ophthalmologists and optometrists must remain vigilant, recognizing that SCLs-related complications may pose a threat to vision[3-4,39-41]. Hypoxia was identified as the primary cause of complications associated with the use of glass and PMMA SCLs. Tan *et al*[42] reported on a study involving 517 eyes that wore PMMA SCLs. They discovered that the most prevalent complications were neovascularization (13.3%) and corneal edema (7.4%), both attributable to corneal hypoxia. Subsequently, 118 eyes from the original cohort were refitted with gas-permeable SCLs, enabling oxygen diffusion through the lens. This led to improved outcomes, significantly reducing complications related to corneal hypoxia[43]. However, these lenses introduced a new set of challenges, including susceptibility to lens deposits, breakage, and suboptimal surface wetting characteristics. The ongoing advancement of gas-permeable (GP) materials and manufacturing techniques continues to enhance the clinical performance of SCLs[2,44]. Complications associated with wearers of modern high Dk SCLs designs encompass infection-related, inflammation-related, and hypoxia-related issues. Therefore, improving the fitting skills of SCLs fitting personnel, increasing the awareness of SCLS related complications, and educating patients on the correct use of SCLs are still the key measures to prevent the complications[27,37,45].

This study is subject to several limitations. First, our data exclusively relied on information from WOSCC. While this database offers comprehensive publication metrics suitable for bibliometric analysis, it is possible that relevant studies from other international databases, such as Scopus and PubMed, may not have been included. Second, our inclusion criteria were centered around studies published in English, potentially introducing a language-based selection bias. Third, we acknowledge that the number of citations an article receives does not offer a complete assessment of its quality. For example, some high-quality literature may not have been thoroughly examined due to late publication dates or insufficient citations. Additionally, self-citations may introduce bias. Despite these limitations, our study provides valuable insights into future research trends and hotspots within the field of SCLs to a certain extent.

In conclusion, SCLs were the pioneering type of contact lens and remain prescribed to this day. This bibliometric analysis complements the historical archive detailing the evolution of SCLs. Utilizing CiteSpace and VOSviewer software for visual analysis, research on SCLs shows a consistent annual growth. Globally, the USA leads in this research. Among research institutions, the Mayo Clinic boasts the highest number of publications. Enhanced cooperation and communication between countries and institutions are imperative. Deborah S. Jacobs stands out as a prominent contributor with the highest citations in the field of SCLs. The majority of articles on SCLs originate from internationally influential journals, underscoring the significant attention garnered by this subject. Currently, research on SCLs predominantly centers around indications, novel materials, fitting methods, clinical outcomes, and potential complications, areas that will continue to be focal points in future research.

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Authors' contributions: Gao J and Xu Y had full access to all the data in the study and take responsibility for the integrity of the data and the accuracy of the data analysis. Concept, design, acquisition, analysis, and interpretation of data: Gao J and Xu Y.

Conflicts of Interest: Gao J, None; **Xu Y,** None.

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