• Bibliometric Research •

A bibliometric analysis of publication trends in strabismus over the past 30y

Yi-Han Zhang[1,2,3], *Ying Guo*[1,2,3], *Shu-Jie Zhang*[1,2,3], *Chen Zhao*[1,2,3]

[1]Eye Institute and Department of Ophthalmology, Eye & ENT Hospital, Fudan University, Shanghai 200031, China
[2]Key laboratory of Myopia and Related Eye Diseases, NHC; Chinese Academy of Medical Sciences, Shanghai 200031, China
[3]Shanghai Key Laboratory of Visual Impairment and Restoration, Shanghai 200031, China
Co-first Authors: Yi-Han Zhang and Ying Guo
Correspondence to: Chen Zhao and Shu-Jie Zhang. Eye Institute and Department of Ophthalmology, Eye & ENT Hospital, Fudan University, 83 Fenyang Road, Shanghai 200031, China. dr_zhaochen@fudan.edu.cn; shujiezhang@fudan.edu.cn
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Abstract

• **AIM:** To summarize publication trends in the field of strabismus over the past 30y and predict future research hotspots.

• **METHODS:** A total of 2915 English-language articles and reviews on strabismus, published between 1993 and 2022, were retrieved from the Web of Science Core Collection. Bibliometric analyses were performed using VOSviewer and CiteSpace software to explore publication trends, as well as the contributions and collaborative networks of countries/regions, authors, institutions, and journals.

• **RESULTS:** The annual number of publications on strabismus showed a consistent upward trend. The United States (USA) maintained a leading position in this research field while Republic of Korea and China emerged as rapidly advancing contributors over the last decade. The University of California, Los Angeles ranked as the most productive institution, and Jonathan M. Holmes from USA was the most productive author. *Journal of AAPOS* was the leading journal with the most strabismus publications, whereas the two most highly cited articles were both published in *Ophthalmology*. Co-occurrence analysis identified pivotal keywords and burst terms, including intermittent exotropia (IXT), acute acquired comitant esotropia (AACE), functional magnetic resonance imaging (fMRI), and surgical treatment, which were confirmed as predominant and frontier topics.

• **CONCLUSION:** This study provides a comprehensive bibliometric analysis of strabismus research, revealing the evolution of research hotspots over the past 30y and outlining several cutting-edge directions for future investigation.

• **KEYWORDS:** bibliometric analysis; strabismus; intermittent exotropia; strabismus surgery; functional magnetic resonance imaging; research trends
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INTRODUCTION

Strabismus refers to a large category of diseases in which the vision axes are not parallel and the coordinated movements of the extraocular muscles are disrupted. Besides its impact on appearance, strabismus leads to amblyopia, loss of stereopsis, and psychosocial problems, affecting the quality of life. Strabismus has a high prevalence (estimated to be 1.93% worldwide[1]) and alters spectra over time and among different ethnic groups[2-7]. Strabismus can be an ocular manifestation of a systemic disease or secondary to structural and/or functional damage to nerves, extraocular muscles, or orbital tissues; however, the majority of strabismus is primary and occurs most often in children. Approximately 5% of normally developing children develop strabismus[8]. Although the diagnostic criteria for strabismus are relatively clear, mainly based on the alternate cover test[9], research on its mechanism is inconclusive[10]. There is a lack of well-developed hypotheses on the relationship between the natural history of strabismus and possible pathogenic factors, such as gene mutation, refractive status, binocular vision, and control from the visual center[11-14]. There are also challenges associated with treatment. Surgery is always the primary option for strabismus intervention. There have been some dose-effect formulas for surgical design based on the experience of surgeons[15], but a reasonably designed procedure may also bring about unsatisfied outcomes due to individual variances. In patients with basic horizontal comitant strabismus, the reported success

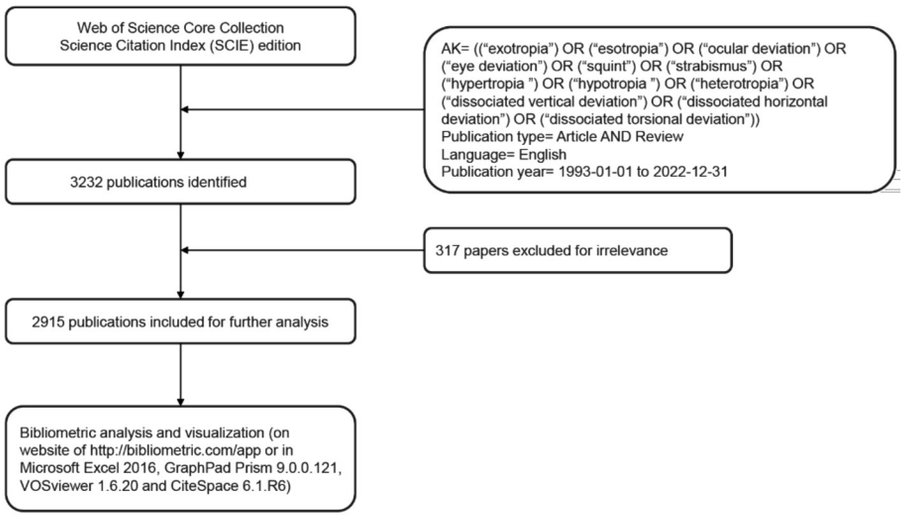

Figure 1 Flow chart of the data collection and analysis.

rates after long-term follow-up were lower than 60%[16-18]. On the other hand, surgery for complex types of strabismus would be more challenging because of the uncertain dose-effect relationship[19]. Inconsistency in efficacy is also present in non-surgical treatments[20].

Based on the above, an overview of relevant publications in recent years may provide a significant boost for strabismus research. Bibliometric analysis is a comprehensive tool to address this issue by summarizing and simplifying the publications of different branches in a given field, and providing a clearer perspective of its future direction[21]. In this article, we resorted to bibliometric analysis to identify the main subjects, countries and regions, affiliations, authors, and journals of strabismus articles. We concluded several long-standing and recent hotspots within the study of strabismus, and made recommendations for future research priorities.

MATERIALS AND METHODS

Ethical Approval Approval was obtained from the Institutional Review Board of Eye & ENT Hospital, Shanghai Medical School, Fudan University and the approval number is 2022142.

Publication Search and Data Collection Publication search was performed via the Web of Science (WOS) database within the Web of Science Core Collection, Science Citation Index Expanded (SCIE) edition at 2023.10.17. The keywords were “((“exotropia”) OR (“esotropia”) OR (“ocular deviation”) OR (“eye deviation”) OR (“squint”) OR (“strabismus”) OR (“hypertropia”) OR (“hypotropia”) OR (“heterotropia”) OR (“dissociated horizontal deviation”) OR (“dissociated vertical deviation”) OR (“dissociated torsional deviation”))” in author keywords. A total of 3232 papers (articles or reviews) in English published between 1993 and 2022 were identified for manual screening. Totally 317 papers that did not focus on strabismus as the main subject, such as articles on clinical trials of pediatric surgical anesthesia management in strabismic children, or case reports on cranial trauma, cranial surgery and systemic genetic syndromes in which strabismus was a concomitant symptom with little attention and no intervention, were additionally manually excluded. Finally, 2915 papers were included for further analysis (Figure 1). Data on publication year, countries or regions, citations, and authors of each relevant paper, as well as the H-index of each research team, were also acquired from WOS.

Bibliometric Analysis Data on publication contributions were analyzed in GraphPad Prism (v. 9.0.0.121, GraphPad Software, California, USA), http://bibliometric.com/app, and Microsoft Excel 2016 (Microsoft, Washington, USA). To better match the curve of cumulative publication number better, we used the prediction model $f(x)=ax^4+bx^3+cx^2+dx+e$. Maps of keyword co-occurrence networks were generated using VOSviewer (v. 1.6.20, Centre for Science and Technology Studies, Leiden)[21] and CiteSpace (v. 6.1. R6)[22]. In the VOSviewer analysis, the occurrence threshold of exhibition was set to 11; for the CiteSpace analysis, the time slice was one year, while the scale factor k was set to 25.

RESULTS

Trends in Publication Output and Contributions of Nations and Regions The total amount of publications related to strabismus has exponentially increased over the past 30y (Figure 2A). Of these, the USA contributed the most publications (944, 32.4%), followed by Republic of Korea (325, 11.1%) and China (306, 10.5%; Figure 2B). American and Asian countries contributed 42.5% and 38.0% of the publications, respectively. In addition, the H-index of the USA is also way ahead of other countries, claiming its leadership in this field (Figure 2B). Totally 83.8% of the papers were contributed by the top 10 countries with the highest number of published works. Notably, the USA has maintained a

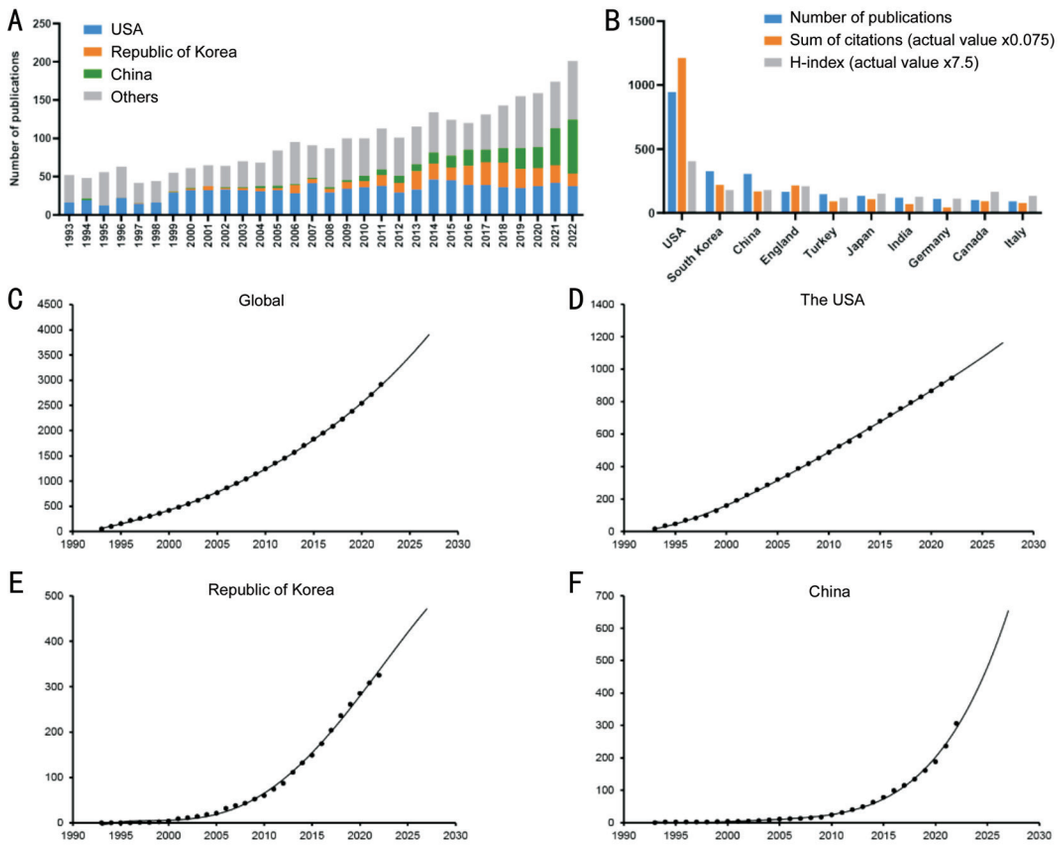

Figure 2 Annual publication output and country contributions A: The publication amount of each year and the corresponding proportion of the USA, Republic of Korea, China and the others. B: The number of publications and citations, as well as H-index of top 10 countries in term of publication amount in the strabismus field. C-F: The growth trends of cumulative publication number globally (C), in the USA (D), Republic of Korea (E) and China (F), over the recent 30y and the matched curves, respectively.

production of 40 publications per year for the last 15y, contributing the most papers for each year in 2020 and before (Figure 2A). On the other hand, Republic of Korea and China have made rapid progress in this field over the last decade. China has surpassed the USA in annual publication volume from 2021 to become the top of the list.

The increase in strabismus publications is predicted to continue over the next 5y (Figure 2C). Undoubtedly, the USA should retain its leadership in publication number and maintain steady growth (Figure 2D to 2F). Notably, China has shown the most rapid increase in recent five years, and is expected to double the total publication amount over the next five years (Figure 2F).

The co-occurrence of 22 countries and regions (with an overall publication number over 20) was analyzed using VOSviewer[22] (Figure 3A). Countries from different continents exhibited a certain degree of clustering, which aligns with the specific spectrums and therapeutic options for strabismus among various ethnic groups.

Contributions of Institutions and Authors Over the past 30y, the University of California, Los Angeles has been the leading institution with the most relevant publications (208, 7.14%), followed by Mayo Clinic (155, 5.32%) and Seoul National University (137, 4.70%). The top 15 institutions are listed (Figure 3B).

In the past three decades, 457 papers (15.7%) were published by the top ten authors in the field of strabismus. Top three authors with the most publications are Jonathan M. Holmes (40 as the corresponding author and 13 as the first author), Jeong-Min Hwang (52 as the corresponding author and 3 as the first author) and Brian G. Mohney (29 as the corresponding author and 10 as the first author). All the top ten authors are from the USA or Republic of Korea; three of them are affiliated to Mayo Clinic and three are affiliated to Seoul National University (Table 1).

The collaboration between researchers was also analyzed using VOSviewer (Figure 3C). Node size represents the contribution of the investigators individually, whereas line thickness indicates the correlation strength between the connected authors.

Distribution in Journals Nearly half (1432, 49.1%) of the relevant publications were published in the top 10 periodicals, including *Journal of AAPOS* (454, 15.6%), arguably the most authoritative periodical in the field of strabismus. *Journal of Pediatric Ophthalmology & Strabismus* (248, 8.5%) ranked second, and *American Journal of Ophthalmology* (119, 4.08%) ranked third (Figure 3D).

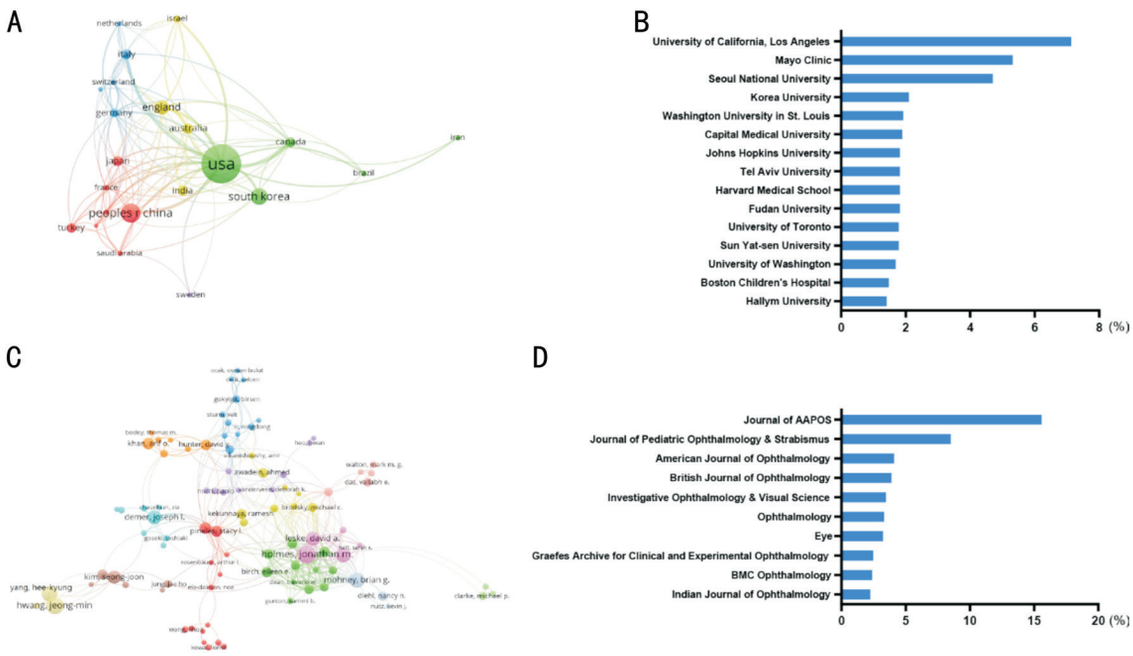

Figure 3 Co-occurrence and distribution of strabismus publications A: Co-occurrence of countries/regions; B: Top 15 institutions with the largest publication amount on strabismus; C: Co-occurrence of authors; D: Top 10 journals with the most relevant publications.

Table 1 Top 10 authors with the most publications on strabismus

Author	Country	Affiliation	Publication amount	Citation amount
Jonathan M. Holmes	USA	University of Arizona	68	844
Jeong-Min Hwang	Republic of Korea	Seoul National University	65	439
Brian G. Mohney	USA	Mayo Clinic	50	1136
Seung-Hyun Kim	Republic of Korea	Korea University	42	184
Sarah R. Hatt	USA	Mayo Clinic	41	629
Joseph L. Demer	USA	University of California, Los Angeles	40	365
Hee Kyung Yang	Republic of Korea	Seoul National University	40	170
Eileen E. Birch	USA	University of Texas	39	655
David A. Leske	USA	Mayo Clinic	39	557
Seong-Joon Kim	Republic of Korea	Seoul National University	33	176

In 2014, a high-quality article (with the highest impact factor) by Gulati *et al*[23] was published in *JAMA Pediatrics*. It's a longitudinal cohort analysis with 38 055 otherwise healthy premature infants included. Infants born with very low birth weight were found to suffer a large increase in strabismus risk. Thus, the team called for updates to existing guidelines for more optimized health monitoring of preterm babies. What's more, a high-quality journal *Survey of Ophthalmology* published only 14 relevant papers, yet two of them became the top 10 in terms of citation amount discussed below, suggesting the impact of the periodical itself on the citations of the articles.

Distribution of Citation Totally 20 623 non-self-citations out of 32 959 relevant citations since 1993 were revealed by the WOS citation report. Each publication was cited an average of 7.07 times. The USA contributed the most citations (16 180, 13 721 without self-citations) and the highest H-index (54; Figure 2B) in the last three decades. Interestingly, England ranked second in both the H-index (28) and non-self-citations (2719), despite its fourth ranking in terms of the overall publication amount, half that of Republic of Korea and China. This phenomenon might relate to the early start of England in the field of strabismus. Republic of Korea ranked third, with 2924 citations, 2327 non-self-citations and an H-index of 24.

The paper with the highest citation count has received 307 citations, while the least ones have yet to receive any. All related papers were divided into three groups based on citation frequency: the high citation frequency group (more than 200 citations), medium citation frequency group (more than 100 but no more than 200 citations), and low citation frequency group (no more than 100 citations). The vast majority of publications were in the low citation frequency group, while 19 papers were in the medium-frequency group and only two papers were cited in a high frequency (Figure 4A).

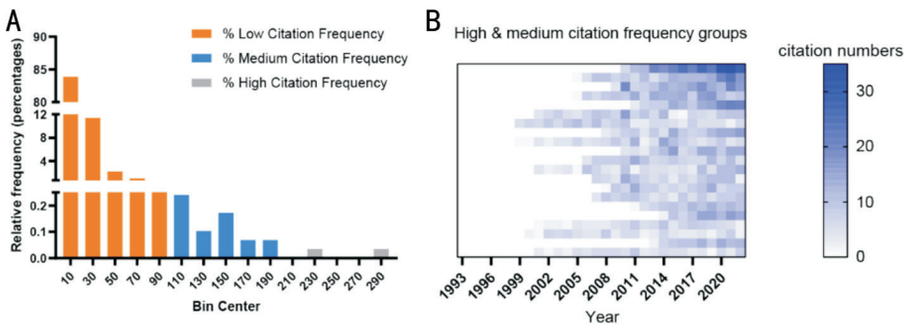

Figure 4 Distribution in citations and publication years A: The distribution of total number of citations; B: Heatmap of citation distribution across past 30y of publications in high & medium citation frequency groups.

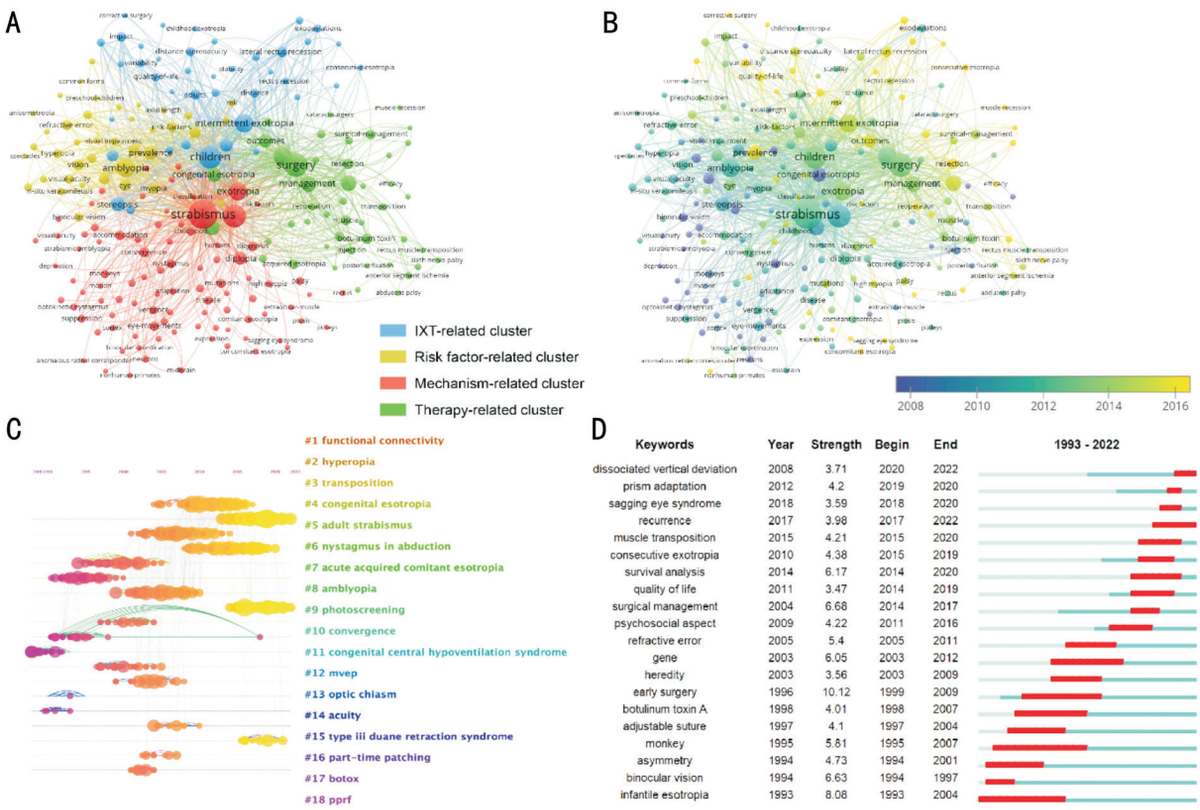

Figure 5 Result of keyword and burst term analysis A: Keywords in the strabismus field extracted *via* VOSviewer and clustered by co-occurrence. B: Keywords extracted by VOSviewer and colored by the average time point of occurrence. C: Keywords analyzed and clustered by CiteSpace with corresponding topic outlined for each cluster and sorted by time zone. D: Top 20 burst terms in the strabismus field over the last 30y. MVEP: Multifocal visual evoked potential; PPRF: Paramedian pontine reticular formation; IXT: Intermittent exotropia.

Top ten of the most frequently cited publications are displayed in Table 2. It's worth mentioning that both 2 papers in high citation frequency group were published in an authoritative and classic periodical, *Ophthalmology*. Prof. Mohney, one of the top three most productive authors, is also the most impactful author (with the highest total citation count) and was a co-author of the second most cited paper.

We generated heat maps to understand the distribution of citations across years for high and medium citation frequency groups (Figure 4B). In this heatmap, each row represents a paper, and each column represents a year, respectively.

Co-occurrence Analysis of Keywords and the Burst Terms Keyword analysis reveals the words that are used most frequently within the field of strabismus and how they relate to each other, providing clues for emerging trends and hotspots. We analyzed noun words with more than 11 occurrences in these 2195 relevant papers using VOSviewer. After merging duplicates and excluding irrelevant words, we obtained 218 keywords. These words can be roughly classified into four clusters based on their co-occurrence (Figure 5A). Except for the blue cluster, which is specifically related to intermittent exotropia (IXT), the remaining three clusters can be summarized as risk factor-related cluster (yellow), mechanism-related cluster (red), and therapy-related cluster (green).

The nodes are colored based on the average time point of occurrence (Figure 5B). Yellowish words (*e.g.*, quality-of-life,

Table 2 Top 10 publications in the strabismus field with the most citations

Title	Corresponding authors	Journal	Publication year	Total citations
Prevalence of amblyopia and strabismus in white and African American children aged 6 through 71mo: the Baltimore pediatric eye disease study	James M. Tielsch	*Ophthalmology*	2009	307
Incidence and types of childhood exotropia - a population-based study	Brian G. Mohney	*Ophthalmology*	2005	221
Prevalence and risk factors for common vision problems in children: data from the ALSPAC study	C. Williams	*British Journal of Ophthalmology*	2008	199
Amblyopia characterization, treatment, and prophylaxis	Kurt Simons	*Survey of Ophthalmology*	2005	198
Prevalence of amblyopia and strabismus in young Singaporean Chinese children	Audrey Chia	*Investigative Ophthalmology & Visual Science*	2010	166
Periventricular leukomalacia: an important cause of visual and ocular motility dysfunction in children	Gordon N. Dutton	*Survey of Ophthalmology*	2000	164
Instrument-induced measurement errors during strabismus surgery	Arthur L. Rosenbaum	*Journal of AAPOS*	1999	154
The effect of amblyopia on fine motor skills in children	Ann L. Webber	*Investigative Ophthalmology & Visual Science*	2008	149
The negative psychosocial impact of strabismus in adults	Angela N Buffenn	*Journal of AAPOS*	1999	147
The functional significance of stereopsis	Anna R. O'Connor	*Investigative Ophthalmology & Visual Science*	2010	144

consecutive esotropia, and sagging eye syndrome) appeared more recently, whereas larger and darker green nodes, such as surgery, children, and amblyopia, might be topics of constant interest in the strabismus community.

Publications were also analyzed using CiteSpace[24] with a time slice of 1y (Figure 5C). The modularity *Q* was 0.795, reflecting the significance of the network, and the weighted mean silhouette S was 0.8611, indicating that the clusters are reasonable. In these two maps, each node represents a keyword, whereas each line (both the colored and the gray ones) for the co-occurrence relationship. Totally 1248 unique nodes, 4763 lines were contained, and 19 main clusters were produced.

In the map sorted by time zone (Figure 5C), the horizontal position of each node represents the initial corresponding keywords co-occurred, while the size reflects the frequency. As shown, IXT, functional connectivity, and hyperopia are highly topical, with a large bunch of relevant keywords, while IXT, acute acquired comitant esotropia (AACE), and part-time patching are at the frontier of current research in the last 10y.

The burst terms were outlined by CiteSpace to understand the dynamic transformations in research focus and current hotspots, so as to predict subsequent trends in the future. After the screening for burst strength, 20 burst terms were listed (Figure 5D), along with the year of the first appearance and the specific time span of burstiness. The last column is a visualization of the corresponding time information. As we can see, the treatment of strabismus, especially surgical treatment, has been a long-standing topic throughout recent 30y. In the earlier period, the pathogenesis of strabismus (binocular vision, heredity, and gene, *etc*.) received great attention, while more recently, research interests in postoperative management as well as complex types of strabismus (dissociated vertical deviation, sagging eye syndrome, and recurrence, *etc*.). These results are also consistent with those obtained using VOSviewer (Figure 5B).

DISCUSSION

Our bibliometric analysis provides clues to the frontiers and future trends in strabismus research. After analyzing the keywords and recent burst terms, from the perspectives of disease type, mechanism, diagnosis and management, we outlined several foci, such as IXT, AACE, children, stereopsis, functional magnetic resonance imaging (fMRI), surgery, and other complementary non-surgical treatments. These results provide an overview of the progress in strabismus over the past three decades and could predict future research directions.

Contributions of Countries and Regions, Authors, Institutions, and Journals The number of publications on strabismus has increased exponentially (Figure 2A). American and Asian countries and regions have played relatively important roles in this field. It is understandable that the USA is the most influential country (Figure 2B) because it has a probably higher prevalence of strabismus[25], an early start in relevant research, and a bunch of authoritative journals (such as the top three periodicals with the most strabismus publications in Figure 3D). All of this has allowed it to maintain a leading position in every respect over the past years. Republic of Korea, with the second ranking in terms of contributions to strabismus publications, on the other hand, has a well-developed cosmetic industry. Higher cosmetic demands have provided a unique opportunity and this could explain its dominance in strabismus research in Asia. It has to be highlighted that China has exhibited the fastest growth in recent years. Despite its relatively late beginning, with the total number of publications not exceeding 100 until 2017, it has almost caught up with Republic of Korea in terms of publication amount in only five years (Figure 2F).

Top journals for strabismus were defined in our study. Interestingly, *Journal of AAPOS* has a relatively low impact factor, but it does not stop it from holding the most relevant publications (454, 15.6%; Figure 3D) and being far ahead

in citation amount (3316) as well. *Journal of AAPOS* is the official periodical of the American Association for Pediatric Ophthalmology and Strabismus (AAPOS), the later playing a pivotal and authoritative role in the field of strabismus. It is quite common that the impact factor of an ophthalmology periodical is not indicative of its academic status in the corresponding field.

The number of citations and the H-index can indicate the influence of a certain research team to some extent[26-27]. Highly cited articles, authors, and institutions would be more vocal and may guide future research. The vast majority of strabismus papers remain less frequently cited (Figure 4A), and it is alarming to note that despite of the rapid growth in publication quantity, China is weaker in citation number and H-index than England, which holds the fourth position in total paper amount. The Chinese institution with the most relevant publications was ranked tied for seventh globally (Fudan University, 53 publications; Figure 3B), with far fewer citations than the same ranked institutions, while the Chinese journal with the most relevant publications was ranked 19th globally (*International Journal of Ophthalmology*). This might be attributed to the pursuit of article quantity in Chinese hospitals in earlier times, coupled with undeveloped healthcare record systems. However, with the emphasis on article quality as well as the growth of strabismus research groups and improvement of the medical environment, we can expect more high-quality studies from China in the near future.

Collaborations Between Countries and Regions, Authors, and Groups It makes sense that the co-occurrence analysis of countries and regions reflects a closer connection between countries from the same continent (Figure 3A). Previous epidemiologic studies have reported diversity in disease spectra in different populations. Exotropia is indicated to be more common in Asian children, while esotropia is less when compared to children in Western countries[28-30]. The dose-effect relationship of strabismus surgery may vary in different ethnic groups based on clinical experience.

In addition, the analysis on collaboration between authors indicated that Jonathan M. Holmes, the most productive author, cooperates quite closely with others. Three of the top ten authors from Mayo Clinic, as discussed above (Table 1), exhibited a close connection (Figure 3C), as did three scholars from Seoul National University (Figure 3C). Clinical studies with large sample sizes often require collaboration across groups and institutions and closer communication can lead to more meaningful results with more generalizable implications.

Keywords and Hotspots on Strabismus The main findings of these relatively more frequently cited publications can be summarized as the prevalence, types, and associated factors of strabismus derived from retrospective studies with large sample sizes and long spans of time.

Among all the keywords we identified, IXT has been the most discussed over the years (Figure 5), which is intimately related to its high prevalence. In an American report, the prevalence of IXT was 0.86% in children under 11y of age[28], while a Chinese study reported a prevalence of 4.5% in babies aged 36-72mo[29]. The interventions of IXT have always been one of the hot topics. Currently, surgery is the primary advice to restore ocular alignment in patients with large-angle or frequently observed IXT[31-32]. Not surprisingly, nearly half of the hotspots are related to the treatments, especially surgery for strabismus (Figure 5D). It is worth mentioning that keywords such as surgical outcomes, recurrence, consecutive strabismus, and muscle transposition have sprung up around 2017, consistent with the increasing retrospective or prospective studies of surgical outcomes[20,31-33] and the pursuit of more precise surgical design in recent years. Bilateral lateral rectus recession procedure and unilateral recession resection procedure are two basic surgical options for IXT[34], which were proposed as early as approximately half a century ago. As has been enriched (Figure 5A), their dose-response relationship, surgical risks, and corresponding countermeasures[35] have also been extensively studied. The findings are sometimes controversial due to variability in factors such as population, strabismus types (*e.g.*, basic or divergence excess types), and follow-up periods in different studies. In some randomized controlled trials, the bilateral lateral rectus recession procedure has shown more stable therapeutic effects over longer observation periods[36-37], while in others, the unilateral recession resection procedure produced a significantly higher short-term success rate[18,38]. However, due to individual differences and the presence of drift, surgical design strictly based on a formula may still result in short-term or long-term recurrence or overcorrection. After one year of follow-up, the success rate was approximately 42%-74.2%[37,39], while the overcorrection rate ranged from 1.5%[40] to 21%[39]. Further interventions, including secondary surgery, may be required for these patients with suboptimal alignment.

Additionally, non-surgical strategies such as botulinum toxin A injection, patching, binocular single vision training, and glasses are constantly changing the entire landscape of strabismus interventions[20] (Figure 5C). Botulinum toxin A injection is a less invasive treatment with shorter-lasting side effects, and has been reported to be similarly efficacious to surgery, especially for small-angle strabismus[41-42]. It can restore the parallelism of the visual axes and binocular single vision, creating a chance for the central nervous system to regain control of eye position[43]. However, more clinical ophthalmologists hold reservations about this therapy because of concerns, such as the lack of long-term data and some uncertainty about dosing.

Preoperative and postoperative binocular single vision training as well as patching (occlusion of the dominant eye or alternate occlusion in children with no dominancy relationship found[44]) may be helpful in improving the surgical success rate[16]. The development of handheld smart devices has also provided convenience for vision training. Overall, we need more and longer-term researches on surgical outcomes to optimize the timing, choice of procedures, and postoperative managements for IXT and other complex strabismus, and the refinement of emerging remedies is also expected.

As for the terms burst recently, we can note "functional connectivity" (Figure 5C), an essential dimension in resting-state fMRI to describe the functional integration between brain regions[45]. Disrupted brain network leads to abnormalities in binocular vision and the oculomotor system, and is believed to be one of the fundamental mechanisms for comitant strabismus[10]. Rapidly developed fMRI technology has provided a new perspective for the study of the etiology of strabismus related to stereopsis and the central nervous system. Compared to conventional MRI, which provides a look at orbital and cranial structures, as well as thickness, starting and ending points of extraocular muscles, fMRI is able to show how different brain regions function and interact with each other. Dorsal visual pathway is frequently reported to be impaired in strabismus patients by fMRI[14,46]. However, the detailed changes in different studies are not always consistent because of the large heterogeneity of the included subjects[47]. Nishida *et al*[48] thought that regions from the dorsal portion of the occipital lobe to the superior parietal lobule were responsible for stereopsis-processing, while Hu *et al*[14] found functional changes in the fusiform gyrus related to the deviation angle in AACE patients. fMRI also provides an objective dimension for the prediction of stereopsis recovery after strabismus surgery. Xi *et al*[49] revealed a correlation between worse postoperative stereopsis and hypoactivity in the right V3A and left intraparietal sulcus in patients with IXT. In a word, although more clinical practice is required to obtain standardized guidelines, fMRI is a promising aid for mechanistic studies, prognostic assessments, and postoperative management for strabismus, which may become important directions for future research.

Efforts to explore the mechanisms of strabismus have not been limited to examining patients using fMRI. A number of etiologically relevant keywords, such as gene, hereditary, and refractive error, have also emerged in turn. In addition to the earliest proposed mechanism of binocular vision, attention to hereditary and refractive error began approximately 20 years ago and underwent a boost of nearly a decade (Figure 5B). Except for systemic muscle disorders and abnormalities in extraocular muscle development, for which some clear causative genes have been elucidated (*e.g.*, *DMD* for Duchenne muscular dystrophy[50], *KIF21A* for congenital fibrosis of the extraocular muscles type 1, and *PHOX2A* for type 2[51-52]), there is also a complex genetic predisposition in comitant strabismus[53]. After a study of 1462 twin pairs, Sanifilippo *et al*[54] revealed a significantly greater correlation for eso-deviation in monozygotic than in dizygotic pairs. Hyperopia is commonly recognized as another independent risk factor for esotropia[11,55]. Studies have also reported an association between exotropia and astigmatism[11]. Since the strabismus mechanism involves advanced factors, such as eye movement and visual function, small animals cannot always well meet the demands of basic research. Most of the time, experiments on the mechanisms and treatments need to be carried out on large animals. For example, Tychsen[56] reported binocular decorrelation as a cause of infantile esotropia after researches on monkeys. This explains why the keyword monkey co-occurred with other mechanism-related burst terms at an early stage (Figure 5D). To conclude, the pathogenesis of strabismus could be a complex collection including genetic and/or acquired abnormalities, anatomical and/or functional abnormalities, in the sensory and/or the motor systems, both peripherally and/or in the brain itself[10]. The discovery of a clear mechanism will undoubtedly lead to a revolution in strabismus management.

AACE has also been the focus in recent years. AACE is a special type of comitant esotropia characterized by acute onset, diplopia, symmetric eye deviation and movement, which occurs more often in older children and adults with myopia[2]. The increasing use of digital devices and time under indoor quarantine due to the coronavirus pandemic may explain the growing incidence of AACE[57-58]. The etiology of AACE has not yet been fully elucidated. Since narrowing in the range of binocular fusion as well as increased tone of the medial rectus muscle have been observed in AACE patients, it is now thought to be caused by a combination of abnormalities in the extraocular muscles coupled with the visual center[59-60]. fMRI has provided considerable clues for the study of AACE mechanisms related to the primary visual cortex and dorsal pathway, which explains the tendency of co-occurrence between AACE and functional connectivity (Figure 5C). Most patients with AACE have cosmetic and diplopia complaints, placing additional demands on surgical design precision. In clinical practice, the surgical amount of AACE always need to be augmented to promote stereopsis recovery and prevent recurrence[61-62]. Plenty of retrospective clinical studies on the dose-response relationship of AACE surgery have been conducted. Roda *et al*[62] reported an average dose-response of 1.8±0.6 prism diopter per millimeter (PD/mm) in augmented bilateral symmetrical medial rectus recession. As for unilateral medial rectus recession and lateral rectus resection, Zhou *et*

al[2] reported an average dose-response of 5.11 PD/mm for medial rectus and 2.51 PD/mm for lateral rectus in AACE patients with deviation under 30 PD, respectively, with 5.48 PD/mm in additional lateral rectus resection for deviation beyond 30 PD. It is foreseen that topics about the specific pathogenesis of AACE and individualized surgical design will remain hot over the coming years.

Regrettably, non-English publications (*e.g.*, papers in Korean or Chinese) were not included, which also made indispensable contributions to strabismus. Additionally, illustrations, especially those presenting surgical procedures and neural pathways, are an essential part of strabismus publications. Whereas it is difficult for bibliometric analysis tools to extract information from illustrations, some important results may have been missed.

Overall, it is a comprehensive bibliometric analysis of strabismus publications to characterize the distribution of country, institution, author, journal, and citations in the past three decades, and to forecast the publication trends in the future. We identified the pivotal role of the USA in this field, and found that high-quality prospective clinical studies with extensive participants involvement and extended observation periods on highly prevalent types of strabismus were more popular with authoritative journals, which would facilitate the resolution of currently controversial issues and better meet the needs of clinical practice in strabismus. We also summarize the transformation of the research focus in the field of strabismus. While IXT, risk factors, and treatments for strabismus have been longstanding hot topics, in recent years on the other hand, concerns regarding AACE, complicated types of strabismus, as well as the long-term quality of life have continued to increase. These results may help relevant researchers and clinicians to develop a general understanding of the history of the strabismus field, and provide them with better decisions for future research.

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