Original Article

Research trends on stereotactic radiosurgery in brain metastases: a bibliometric analysis from 2013 to 2023

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Background: Brain metastases (BM) are the most common type of intracranial tumor and the leading cause of mortality in patients with systemic cancer. In recent years, stereotactic radiosurgery (SRS) has been widely used in the radiotherapy of BM due to its advantages of high positional accuracy and highly conformal dose distributions. However, this area lacks a bibliometric analysis. This study aims to provide an overview of recent trends and key topics related to SRS for BM treatment over the past decade and to anticipate future directions through bibliometric methods.

Methods: We conducted a search in the Web of Science for publications on SRS in BM treatment from 2013 to 2023. VOSviewer, CiteSpace, and the R package "bibliometrix" were utilized to perform a bibliometric and visual analysis of online publications in this field, focusing on countries/regions, institutions, authors, journals, and keywords.

Results: A total of 2,085 articles were identified in this study, with a steady increase observed in annual publications. The United States (USA) was the most productive country and the core of international cooperation; Mayo Clinic was the institution with the most publications and citations; *Journal of Neuro-Oncology* published the most papers; the most published author was Sahgal A, and Brown PD was the most co-cited author. The latest high-frequency keywords were immunotherapy, survival, prognosis, recurrence, leptomeningeal metastases, and so on. Keyword cooccurrence was used for cluster analysis, resulting in 7 clusters that highlight the emerging frontiers of SRS in BM treatment.

Conclusions: As medical imaging informatics technology continues to advance, research into SRS for BM

treatment has become increasingly in-depth. The immunoadjuvant therapy, biological effective dose, and radionecrosis have emerged as hot topics in recent years. Future work is ongoing to develop and improve artificial intelligence (AI) tools to assist in SRS treatment planning, thus benefiting more BM patients.

Keywords: Stereotactic radiosurgery (SRS); brain metastases (BM); bibliometric analysis; cancer; radiotherapy (RT)

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Introduction

Brain metastases (BM) are the leading type of malignant tumor in the central nervous system (CNS) that spread from primary cancers in other organs, representing approximately 10–30% of all brain neoplasms (1). The emergence of BM signifies the terminal stages of cancer and is often associated with a poor prognosis (2). Furthermore, the neurological impairments caused by space-occupying lesions can significantly impact the quality of life (QOL) of patients with BM. Consequently, there is an urgent need to develop and optimize treatment methods for BM.

Radiotherapy (RT) has been one of the mainstream treatments for treating BM, with whole-brain radiation therapy (WBRT) historically considered the preferred choice, particularly for multiple BM (3). However, WBRT involves a wide irradiation field and carries multiple potential side effects, including cognitive impairment, memory decline, and intellectual loss (4). Currently, the status and application of WBRT are facing challenges and reassessment. With the continuous advancement of RT equipment and medical imaging technology, stereotactic radiosurgery (SRS) has gradually gained attention. Compared to traditional RT methods, SRS delivers a high dose of radiation precisely focused on the tumor area, which can minimize damage to the surrounding healthy brain tissue (5). Hence, the application of SRS has become increasingly widespread over the past decade and grown to be an important part of BM treatment.

As the field of medical research continues to evolve, bibliometrics has emerged as a valuable method for analyzing scientific literature trends and research hotspots. In various subfields of medicine, bibliometrics has found widespread application (6). Despite the significant progress and widespread recognition of SRS technology in treating BM, there are still no relevant studies summarizing the advancements in this area. Given the increasing importance of SRS in treating BM, conducting a bibliometric analysis in this field can not only reveal research trends and patterns over the past decade but also identify major research hotspots and future research directions.

Therefore, the current study aimed to conduct a comprehensive bibliometric analysis of the academic literature on SRS treatment for BM from 2013 to 2023. This study evaluated the number and trends of published literature, the evolution of research topics and keywords, the contributions of major research institutions and authors, and geographical distribution of research. Through bibliometric analysis, we hope to assist in analyzing the development trends of this topic and provide a scientific basis for future research directions and decision-making.

Methods

Data source and search strategy

This study conducted a comprehensive online literature search through the Web of Science Core Collection (WoSCC), as shown in *Figure 1*. The time span for the search extended from 1 January 2013 to 31 December 2023. The following search terms were utilized: Topics = ("Brain Metastases" OR "Cerebral Metastases") AND Topics = ("Stereotactic Radiosurgery" OR "SRS" OR "stereotactic radiotherapy"). All retrieved articles were saved in text formats, yielding a total of 4,016 results.

Inclusion/exclusion criteria

The inclusion criteria were as follows: (I) focused on stereotactic RT for BM; (II) articles and reviews; and (III) the language was English. The exclusion criteria were as follows: (I) publications were meeting abstracts, news, proceeding papers, and so on; (II) studies not centered on BM. Literature was read and screened by two researchers (Z.W. and S.B.) and any disagreement was subjected to the discretion of a third researcher (Y.Z.). A total of 2,085

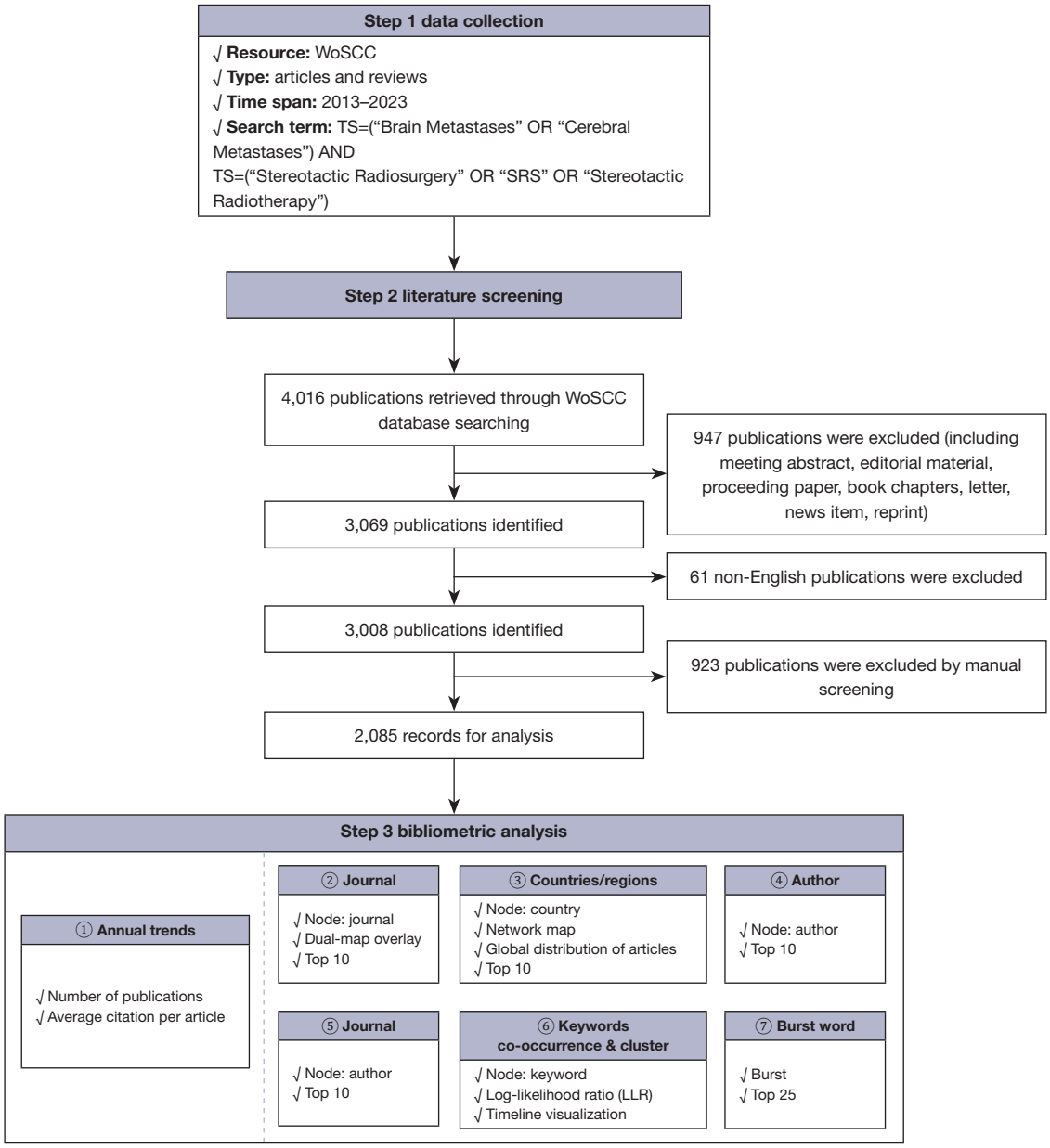


Figure 1 Workflow of this study. WoSCC, Web of Science Core Collection; TS, topics; SRS, stereotactic radiosurgery.

publications were retained.

Data analysis

Citespace (6.2. R3), VOSviewer (1.6.20), and R packages "bibliometrix" (4.3.2) were used to conduct the analyses (7-9).

The Citespace software was employed for keyword emergence, clustering, timeline visualization, keyword burst analyses, and dual-map overlay of journals. In the visual mapping, node size indicates occurrence frequency, with larger nodes representing higher citation rates. The connections between nodes represent collaborative or co-occurrence relationships. A node's purple outer ring signals high betweenness centrality (centrality ≥0.1), suggesting that the more a node acts as a bridge between two other nodes, the higher its betweenness centrality, reflecting the significance of the analysis item represented by the node within the network (10).

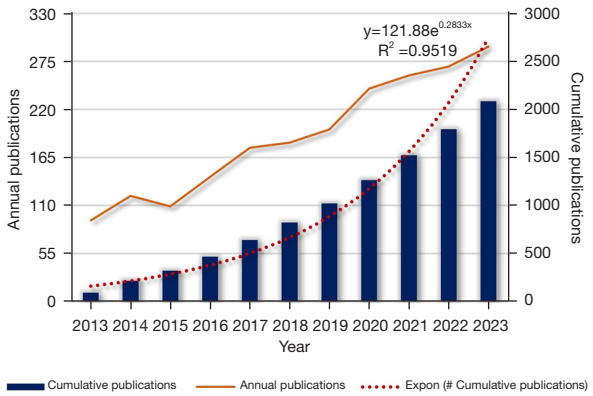


Figure 2 Annual trend chart of publications.

The VOSviewer software was used to primarily conduct the following analyses: collaborative interactions among countries, and regions; citation and co-citation networks of journals and authors. Within the visual maps generated by VOSviewer, a node is considered an item, such as a publication, an author, a country, or an institution. The size and color of a node represent the quantity and category of the item, respectively, whereas the thickness of the lines between nodes indicates the strength of collaboration or frequency of co-citations between items.

The R package "bibliometrix" was applied for all information related to sources, countries, citations, world map, institutions, authors, journals, and keywords.

Results

Overview of publication status

From the WoSCC database, a total of 2,085 papers met the inclusion criteria (*Figure 1*). The number of published papers can reflect the annual changes and future development trends within a research field. As illustrated in *Figure 2*, overall, the annual number of publications has increased over time, with the number of articles published per year rising from 93 in 2013 to 292 in 2023. Based on the model fitting results, the trend of cumulative publication volume exhibits exponential growth ($y=121.88e^{0.2833x}$, $R^2=0.9519$), indicating that the research scale in the field of SRS for treating BM continues to expand and the research interest is not yet saturated, showcasing strong research value.

Countries/regions analysis

A total of 64 countries/regions had published articles in this field. The visualized international collaboration network intuitively displays the production distribution and partnerships among countries/regions (see *Figure 3A*,*3B*). Among these, the United States (USA) ranked first with 1,014 publications, accounting for 48.63% of the total number of papers, making it the primary driving force in the development of this field. It was followed by China (212 publications, 10.17%), Germany (189 publications, 9.06%), Canada (180 publications, 8.63%), and Japan (179 publications, 8.59%), as depicted in *Figure 3C*. The USA had the highest total link strength and close collaborations with China, Germany, and Canada. Additionally, the cumulative annual publication numbers and trends of the top 10 countries are presented in *Figure 3D*.

Institution analysis

The majority of publications came from 2,411 institutions, with the top 10 most active institutions listed in *Table 1*. Mayo Clinic (84 publications, 3,208 citations) was the most productive, followed by the University of Toronto (79 publications, 2,903 citations) and the University of Texas MD Anderson Cancer Center (72 publications, 3,676 citations). The collaboration among institutions is shown in *Figure 4*, which included 169 items organized into 4 differently colored clusters. The red cluster consisting of 43 institutions centered on the Mayo Clinic, University of Toronto, and Texas MD Anderson Cancer Center had the largest cluster.

Journal analysis

A total of 326 journals had published research in this field, with 89 of these journals having more than 5 publications each. The citation network is illustrated in *Figure 5A*, whereas the co-citation network is shown in *Figure 5B*. The node sizes indicate the number of publications and co-citations, with the connecting lines representing citation and co-citation relationships. The top 10 journals had published 735 papers, accounting for 35.25% of all published papers (*Table 2*). The *Journal of Neuro-Oncology* led with 180 publications (8.63%), followed by the *Journal of Neurosurgery and Frontiers in Oncology*, each with 91 publications (4.36%). In terms of impact factors, the *Journal of Clinical Oncology* had the highest with 45.4, confirming the high quality of the top 10 journals. However, regarding total citation frequency and H-index, *the International Journal of Radiation Oncology Biology Physics*

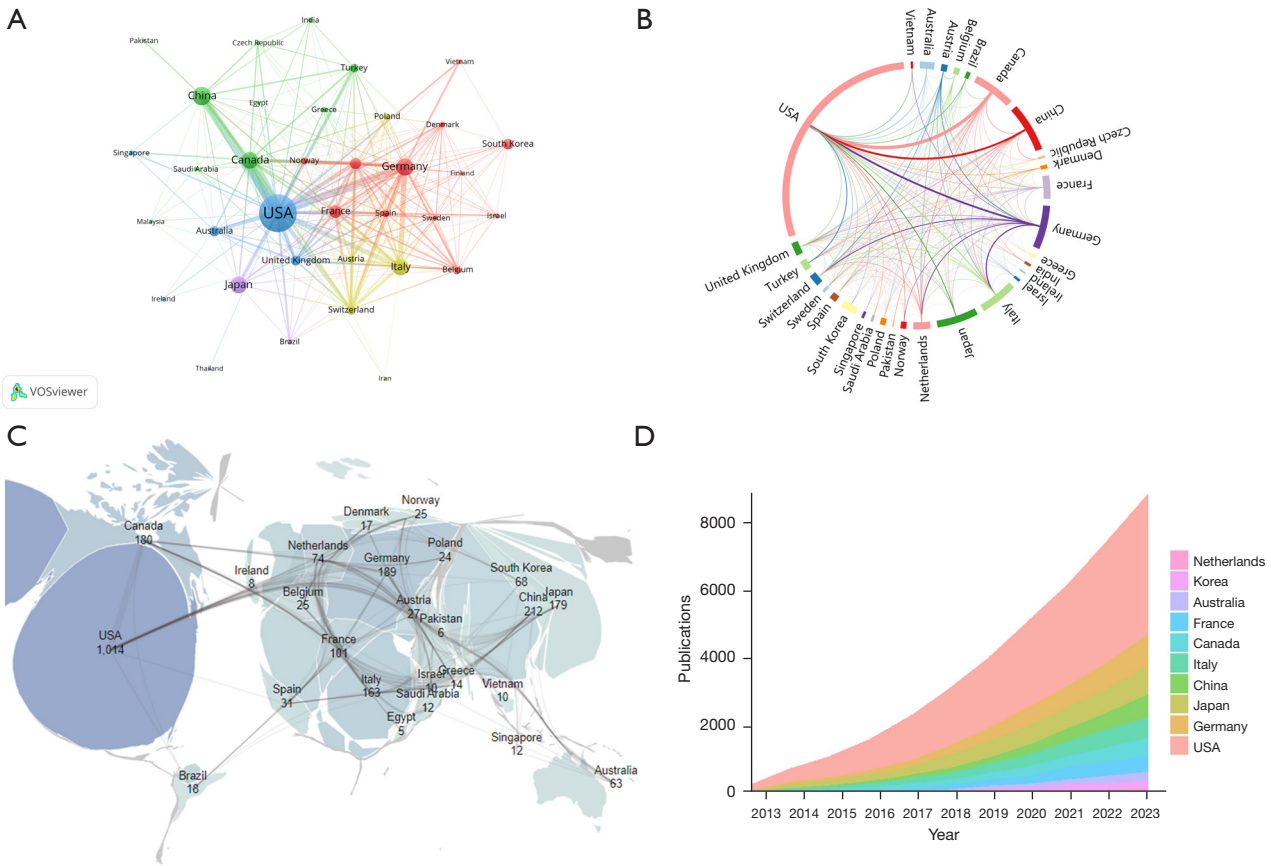


Figure 3 Visualization of countries/regions collaboration and publication trends. (A) Countries/regions network map. (B) Distribution and international cooperation of countries/regions. (C) World map displaying the number of publications. (D) Annual cumulative production trends of the top 10 countries/regions.

Table 1 The top 10 activist institutions

Rank	Institution	TP	TC	ACPP	Country
1	Mayo Clinic	84	3,208	38.19	USA
2	University of Toronto	79	2,903	36.75	Canada
3	University of Texas MD Anderson Cancer Center	72	3,676	51.06	USA
4	Cleveland Clinic	70	2,462	35.17	USA
5	Memorial Sloan Kettering Cancer Center	54	2,637	48.83	USA
6	University of Pittsburgh	51	987	19.35	USA
7	University of Virginia	47	1,109	23.60	USA
8	Yale University	47	2,142	45.57	USA
9	Stanford University	44	1,425	32.39	USA
10	Emory University	43	1,609	37.42	USA

TP, total publications; TC, total citations frequency; ACPP, average citations per publication.

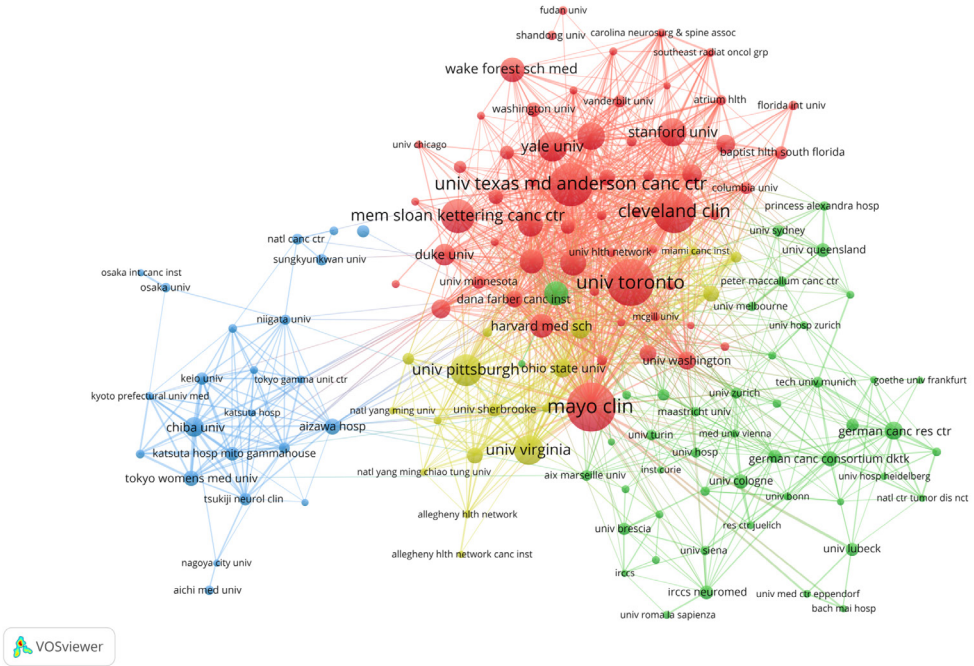


Figure 4 Network map of institution collaboration analysis. univ, university.

led with 4,748 citations and a H-index of 35, making it the most influential journal in the field.

Overlay dual mapping is a visual analytical method used to assess, compare, and contrast the features of publication portfolios. It enables the interdisciplinary nature of research sources and targets, and has been widely applied in bibliometrics (11). *Figure 5C* displays an overlay dual map of journals, showing citing journals on the left and cited journals on the right. Colored pathways represent citation relationships, with 2 main reference pathways marked in green. The citing literature is primarily concentrated in the medicine, medical, and clinical subject categories, whereas the cited literature mainly falls within the molecule, biology, genetics and health, nursing, and medicine subject categories.

Author analysis

A total of 10,341 authors had contributed to the publications in this field. To better illustrate the citation and co-citation relationships among authors, an analysis was conducted on those who had published more than 5 papers. The citation relationships are depicted in *Figure 6A*, whereas *Figure 6B* presents a visual mapping of co-citation relationships among authors, where node sizes reflect the number of publications and co-citations, respectively.

Table 3 lists the 10 most prolific authors. Sahgal A ranked first with 54 publications and an H-index of 24, followed by Brown PD and Chan MD. Notably, Brown PD had the most connections and is the most frequently co-cited author (n=3,222). Other highly cited authors include Sahgal A, Chiang VL, Suh JH, and Vogelbaum MA. These individuals have played significant roles in advancing research and collaboration in the field, contributing substantially to the scholarly dialogue on the treatment and understanding of BM through SRS.

Keyword analysis

Keywords co-occurrence and clusters

Keywords reflect the core concepts and themes of publications, aiding researchers in understanding the development trends and hot topics in specific fields (12). In this study, a keyword co-occurrence network map was constructed with keywords as nodes, where the size of the nodes represents the frequency of keyword occurrence. The network comprises 286 nodes and 356 connections, with a network density of 0.0087, as shown in *Figure 7A*. The 10 most frequently occurring keywords are: “stereotactic radiosurgery” (n=1,503), “brain metastases” (n=1,349),

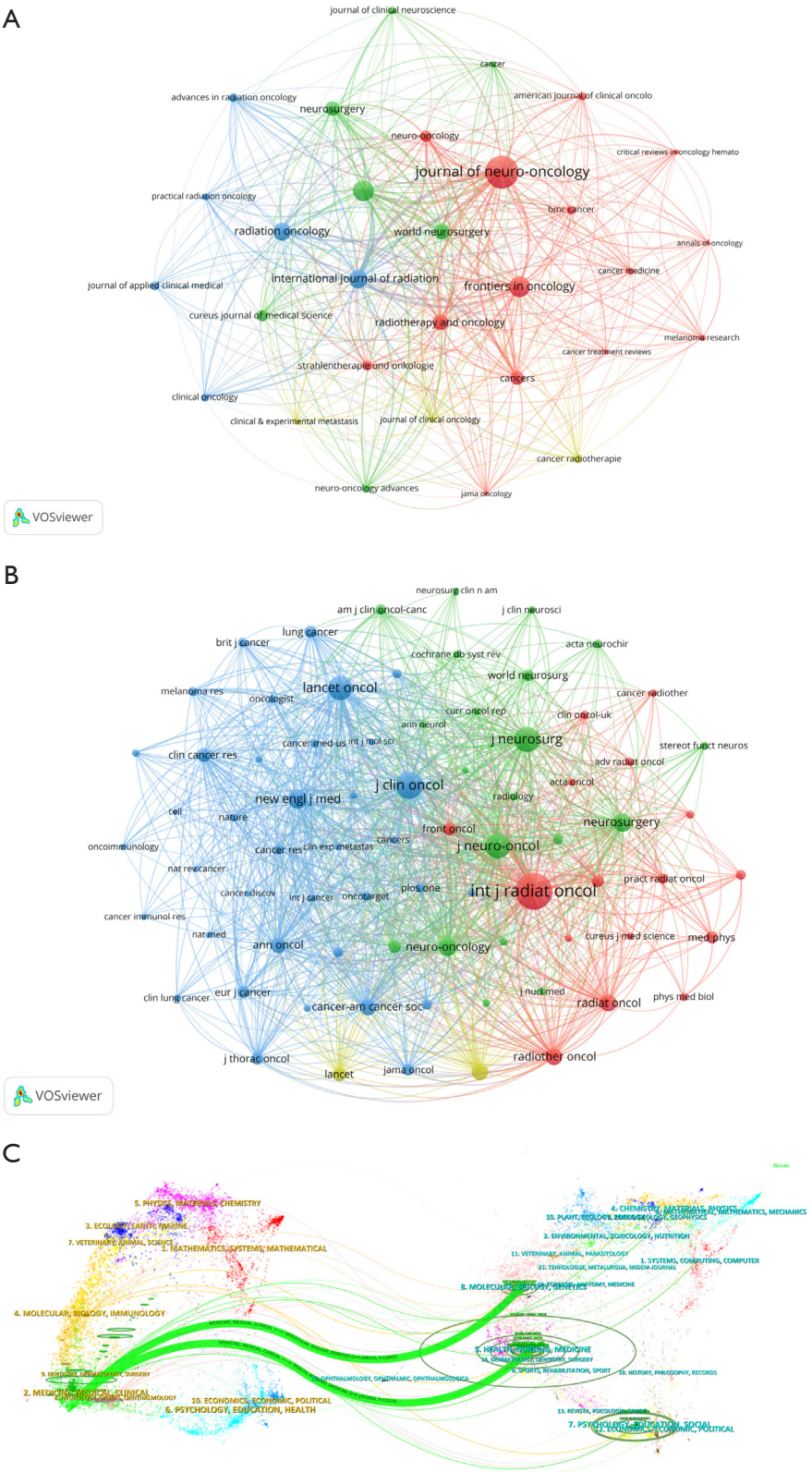


Figure 5 Visualization of journals analysis. (A) Network map of journals analysis. (B) Network map of co-cited journals analysis. (C) The dual-map overlay of journals.

Table 2 The top 10 journals in terms of publication volume

Rank	Journals	TP	TC	ACPP	H-index	IF 2023	JCR
1	*International Journal of Radiation Oncology Biology Physics*	75	4,748	63.31	35	7.0	Q1
2	*Journal of Neuro-Oncology*	180	3,572	19.84	31	3.9	Q2
3	*Journal of Neurosurgery*	91	2,714	29.82	32	4.1	Q2
4	*Neuro-Oncology*	38	1,970	51.84	24	15.9	Q1
5	*Journal of Clinical Oncology*	14	1,883	134.50	14	45.4	Q1
6	*Radiotherapy and Oncology*	60	1,419	23.65	23	5.7	Q2
7	*Radiation Oncology*	72	1,388	19.28	22	3.6	Q2
8	*Neurosurgery*	53	1,206	22.75	22	4.8	Q1
9	*Frontiers in Oncology*	91	1,092	12.00	19	4.7	Q2
10	*World Neurosurgery*	61	618	10.13	15	2.0	Q4

TP, total publications; TC, total citations frequency; ACPP, average citations per publication; IF, impact factor; JCR, journal citation reports.

"radiotherapy" (n=1,183), "gamma knife radiosurgery" (n=464), "survival" (n=454), "immunotherapy" (n=379), "management" (n=337), "surgical resection" (n=325), "prognosis" (n=276), and "tumors" (n=264). The close connections between nodes indicate these areas are significant themes within the research field. Keywords such as "leptomeningeal metastases", "biological effective dose", "recurrence", "neoadjuvant radiosurgery", and "immune checkpoint inhibitor" have centrality >0.1, highlighting their crucial intermediary roles.

Cluster analysis was performed using the log-likelihood ratio (LLR) algorithm based on the keyword co-occurrence network, producing a cluster map shown in *Figure 7B*. The study formed 7 clusters, with a modularity value (Q value) of 0.811 (>0.3) and a mean silhouette value (S value) of 0.9439 (>0.7), indicating effective and reliable clustering that reflects the research hotspots in the field (13). The main research areas involved included: (I) cluster #0 focuses on the types of primary diseases leading to BM, including lung cancer, breast cancer, melanoma, and others; (II) cluster #1 emphasizes clinical trial research in the treatment of BM; (III) cluster #2 focuses on the synergistic effects of SRS combined with immunoadjuvant therapy for treating BM. In recent years, the combined application of SRS and immunotherapy has gained significant attention, bringing new progress in the treatment of BM; (IV) cluster #3 explores comparisons and discussions of different RT techniques; (V) cluster #4 discusses the clinical benefits and prognosis analysis of SRS for BM; (VI) cluster #5 focuses on complications related to SRS treatment, involving radiation necrosis, brain edema, neurological impairments, and somnolence syndrome, among others; (VII) cluster #6 concentrates on the efficient selection of SRS dosage and fractionation schemes.

Keyword bursts

The top 25 terms with the greatest citation bursts, as shown in *Figure 7C*, illustrate the shifting frontiers of research. The blue lines represent the time intervals, whereas the red lines indicate the duration of citation bursts (14). Terms such as "recursive partitioning analysis", "boost", "phase II trial", "gamma knife radiosurgery", and "single metastases" were found to have concluded their bursts, suggesting a decline in their immediate relevance. Conversely, current front-running terms such as "salvage therapy", "stereotactic ablative radiotherapy", "hippocampal avoidance", "Memantine", and "phase III trial" signified high current interest, marking the forefront of the field, and indicating a vibrant area of ongoing research.

Keywords network

The timeline map generated using CiteSpace software based on keyword clustering offers an extensive view of the developmental trajectory of research in the field, capturing the temporal progression of key research topics (15). This timeline is composed of 286 nodes and 356 connections, with color-coded lines representing the emergence time of each cluster. The size of each node reflects its frequency of occurrence, highlighting the significance of certain keywords over time. The keyword timeline visualization

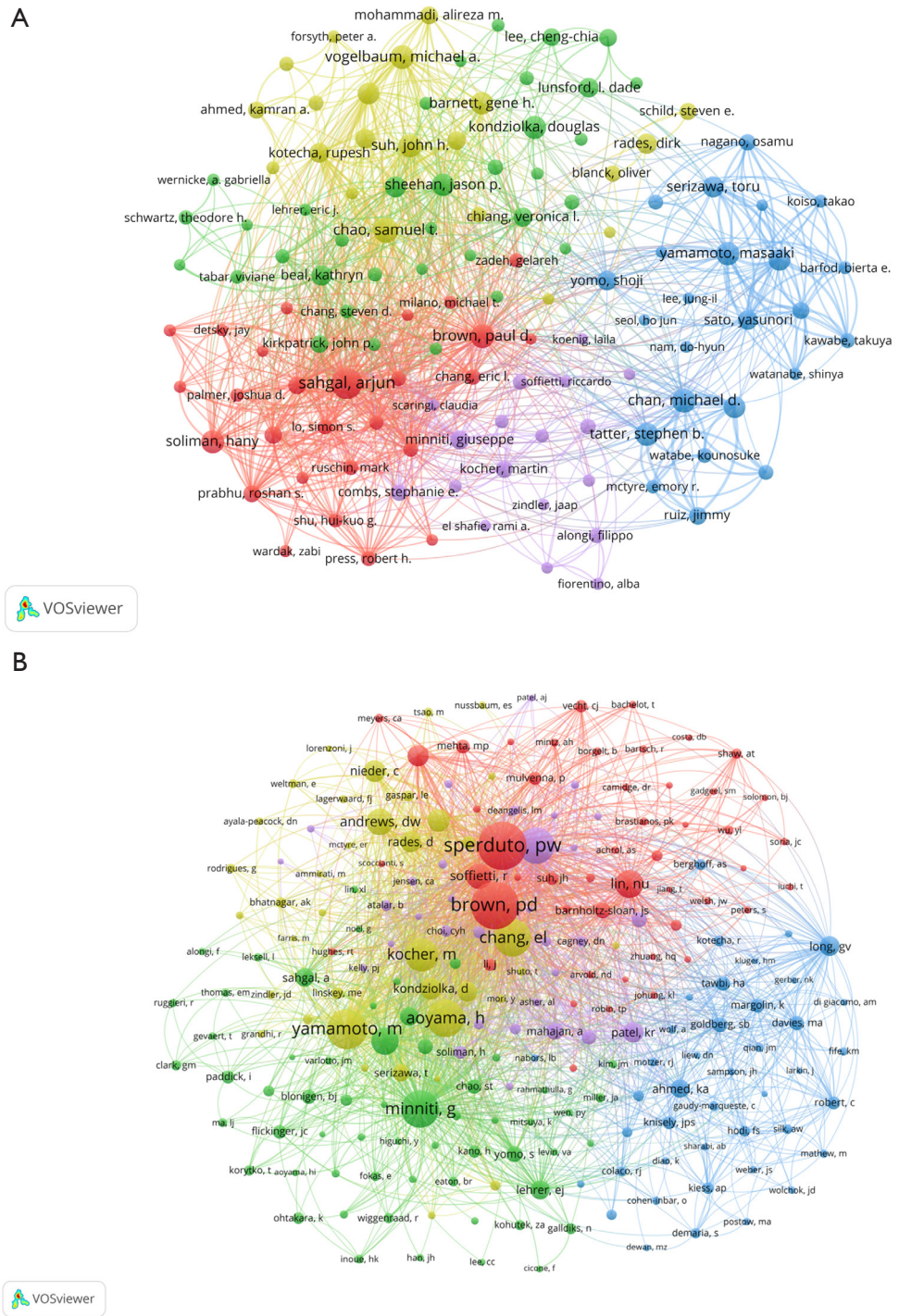


Figure 6 Visualization of authors analysis. (A) Network map of authors analysis. (B) Network map of co-cited authors analysis.

Table 3 The 10 most productive authors

Rank	Author	TP	TC	ACPP	H-index
1	Sahgal A	54	2,358	43.67	24
2	Brown PD	38	3,222	84.79	22
3	Chan MD	37	990	26.76	19
4	Chao ST	38	1,168	30.74	19
5	Barnett GH	30	905	30.17	18
6	Chiang VL	22	1,534	69.73	18
7	Suh JH	33	1,263	38.27	18
8	Tatter SB	33	984	29.82	18
9	Vogelbaum MA	33	1,097	33.24	18
10	Angelov L	25	787	31.48	17

TP, total publications; TC, total citations frequency; ACPP, average citations per publication.

elucidates the evolution of research, transitioning from fundamental validation to clinical optimization (*Figure 8*). Future studies will likely continue to focus on improving survival benefits, managing complications, and conducting clinical trials of new therapies.

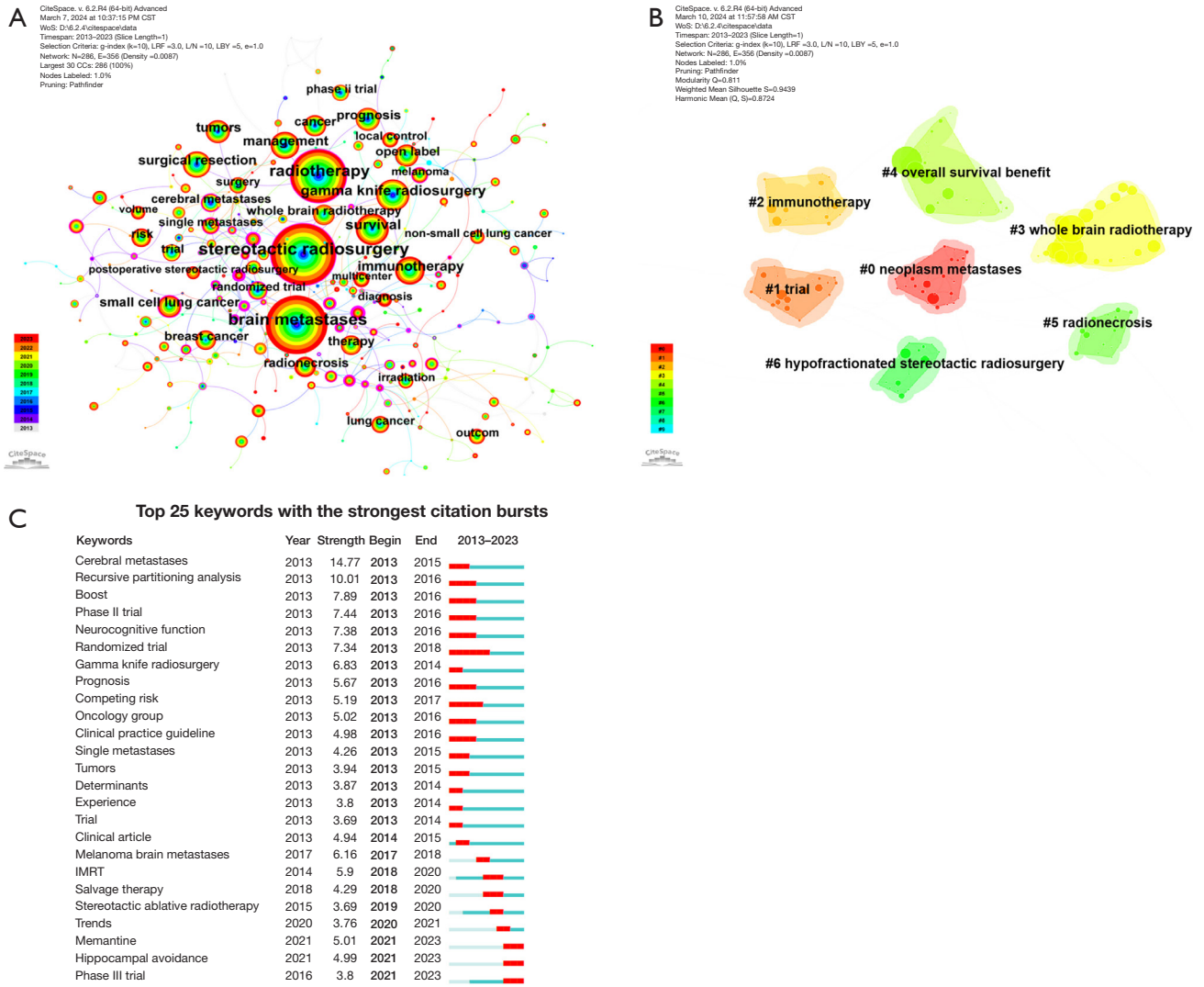
Discussion

This study analyzed the literature on SRS in treating BM based on bibliometric analysis, aiming to delineate the current status of research in this area and provide insights to guide future studies. During the study period, there was a steady increase in the number of research papers published worldwide, as shown in *Figure 2*. Moreover, according to the predictions from exponential growth, there is optimism that more new findings and breakthroughs will emerge in the future.

In the analysis of countries and regions, the USA (1,014 articles) was the most productive country and the core of international cooperation. According to *Table 3* and *Figure 4*, 9 of the top 10 institutions are from the USA, indicating that the USA has played a significant role in advancing scientific progress in this area. From the research institutions, the Mayo Clinic leads the field with 84 publications and the highest total citation count, indicating its considerable influence. Cross-cultural collaboration and exchange are crucial in the context of globalization and digital health. In the future, it is advocated that national institutions and relevant researchers strongly support multi-departmental, multi-center, interdisciplinary collaborations to facilitate in-depth research in the field of SRS in treating BM.

In terms of journal distribution, the *Journal of Neuro-Oncology* published the highest number of articles. In addition, the *International Journal of Radiation Oncology Biology Physics*, the *Journal of Neurosurgery*, *Neuro-Oncology*, and *Radiotherapy and Oncology* may be considered core journals in this field. Researchers are advised to pay close attention to the latest articles published in these journals. From the perspective of authors, an academic community has emerged internationally, centered around prominent figures such as Professor Sahgal from the Department of Radiation Oncology at the University of Toronto and Professor Brown from the Mayo Clinic Anderson Cancer Center. The research focus of Professor Sahgal's group is on the molecular underpinnings, prognostic factors, and therapeutic innovations related to primary CNS tumors (16,17). Professor Brown's group focuses on potential radiation-related complications, with a keen emphasis on preserving cognitive function and minimizing adverse effects (18,19).

Keywords are a highly condensed representation of the core ideas in literature and intuitively reflect the research hotspots and development trends in a scientific field. According to the frequency and centrality, we found that the popular keywords were "survival", "immunotherapy", "management", "surgical resection", "prognosis", "biological effective dose", "leptomeningeal metastases", "recurrence", "neoadjuvant radiosurgery", and "immune checkpoint inhibitor". Cluster analysis was carried out according to the keywords, and 7 clusters were finally formed. From 2013 to 2017, the keywords focused on the diagnosis, indications, and early clinical trials of SRS, which laid the groundwork for its establishment as a standard treatment for BM patients (20,21). Around 2018, the focus of research shifted towards evaluating the safety and efficacy of SRS in treating BM patients (22). This period also emphasized comparing different radiation therapy strategies to optimize treatment plans and improve patient outcomes in terms of survival and QOL (23,24). Since 2020, research in this field has been expanded significantly. The number of papers published each year has remained over 200. The focus has expanded to topics such as immunoadjuvant therapy, biological effective dose, and radionecrosis (25,26). These areas of study have become increasingly mainstream and continue to be actively pursued, suggesting their ongoing relevance and potential to drive advancements in



Keywords	Year	Strength	Begin	End	2013–2023
Cerebral metastases	2013	14.77	2013	2015	
Recursive partitioning analysis	2013	10.01	2013	2016	
Boost	2013	7.89	2013	2016	
Phase II trial	2013	7.44	2013	2016	
Neurocognitive function	2013	7.38	2013	2016	
Randomized trial	2013	7.34	2013	2018	
Gamma knife radiosurgery	2013	6.83	2013	2014	
Prognosis	2013	5.67	2013	2016	
Competing risk	2013	5.19	2013	2017	
Oncology group	2013	5.02	2013	2016	
Clinical practice guideline	2013	4.98	2013	2016	
Single metastases	2013	4.26	2013	2015	
Tumors	2013	3.94	2013	2015	
Determinants	2013	3.87	2013	2014	
Experience	2013	3.8	2013	2014	
Trial	2013	3.69	2013	2014	
Clinical article	2013	4.94	2014	2015	
Melanoma brain metastases	2017	6.16	2017	2018	
IMRT	2014	5.9	2018	2020	
Salvage therapy	2018	4.29	2018	2020	
Stereotactic ablative radiotherapy	2015	3.69	2019	2020	
Trends	2020	3.76	2020	2021	
Memantine	2021	5.01	2021	2023	
Hippocampal avoidance	2021	4.99	2021	2023	
Phase III trial	2016	3.8	2021	2023	

Figure 7 Visualization of keyword analysis. (A) Visual mapping of keyword co-occurrence. (B) Visual mapping of keyword clustering. (C) The top 25 keywords with the strongest citation bursts by CiteSpace. IMRT, intensity modulated radiation therapy.

the field.

Keyword-term burst detection was considered as an indicator of research frontiers or emerging trends over time. In this study, "Memantine", "hippocampal avoidance", and "phase III trial" were keywords that continued to burst as of 2023. This finding indicates that cognitive function protection has garnered significant attention recently and is likely to remain a key area of research and focus in the future. Due to the prolonged life expectancy, maintaining good neurocognitive functioning (NCF) as long as possible is of growing importance. Although numerous studies have reported that the risk of NCF decline in BM patients undergoing SRS is relatively low (5,27,28), it is not completely eliminated, which can have a profound impact on functional status and QOL (29). Therefore, studies comparing SRS to contemporary WBRT with neuroprotective strategies, such as memantine and hippocampal avoidance remain ongoing (30,31). Moreover, with the continuous advances in management strategies, an increasing number of radiation oncologists and neurosurgeons are directing their attention toward disease prevention. Some researchers have indicated that achieving optimal local control and preventing cognitive decline without forming necrosis requires precise BM

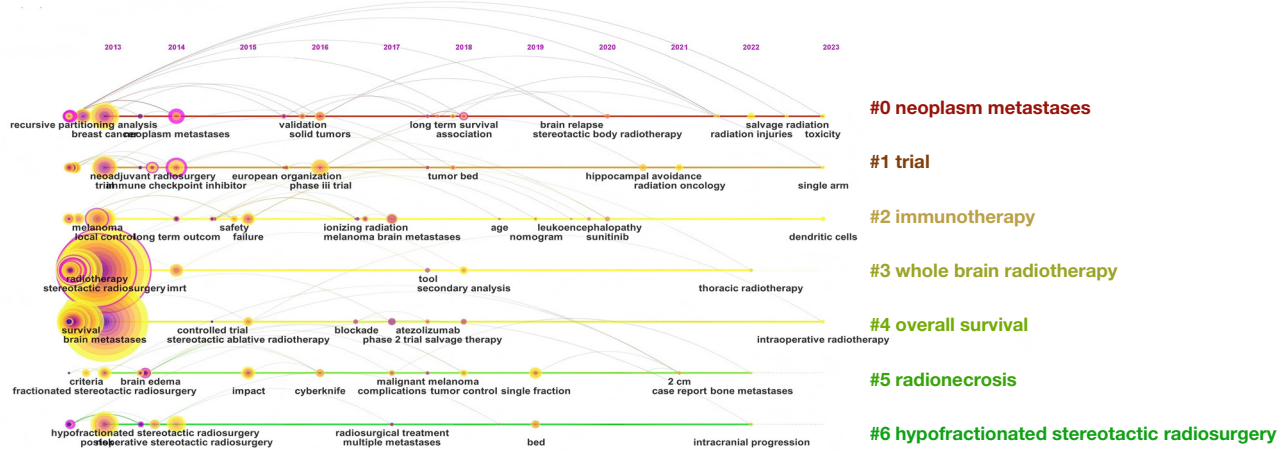


Figure 8 Timeline visualization of co-occurring keywords network (2013–2023).

detection and precise segmentation (32,33). Currently, manual detection of BMs in clinical settings is time-consuming and subject to observer variability. In the era of integrating artificial intelligence (AI) big data, deep learning methods have demonstrated excellent performance in tasks such as detection and segmentation, making the automation of BM delineation in SRS possible (34,35). In the future, the integration of AI into the planning and delivery of SRS treatment may lead to more personalized treatment approaches, thereby minimizing treatment-induced complications and improving outcomes.

There are some limitations to this study. First, the database search in this study was only conducted in WoSCC. Therefore, some representative literature from other databases may have been overlooked. To ensure a more comprehensive bibliometric analysis, it is advisable to integrate multiple data sources in the future. Second, this study only included studies that were published in English, potentially having excluded a few important articles written in other languages. In future studies, considering including research articles written in other languages within the analysis scope could lead to more comprehensive and accurate research conclusions. Third, since the literature search relied on article titles, abstracts, and keywords, the findings might not completely represent studies in the field. Future research can expand the number of studies reviewed by conducting a more thorough search.

Conclusions

Overall, this study provides a comprehensive overview of the development of SRS for BM over the past decade, allowing future researchers to more rapidly pinpoint the leading countries, institutions, and authors in the field. Simultaneously, this study has not only identified numerous high-impact key terms, but also assessed their corresponding temporal information, and scientifically forecasted research hotspots and trends. Future research priorities may involve in-depth exploration of SRS combined with precisely targeted immunotherapy, personalized medicine, and early detection and prevention of radiation-related complications. These areas of investigation hold promise for advancing both clinical practice and scientific understanding within the field. Furthermore, the AI-based brain tumor detection and segmentation module holds tremendous potential. Continuous research and development are crucial to refine AI tools and integrate them into clinical practice to benefit patients with BM.

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