

Mapping the evolution and research landscape of robot-assisted interventions for intracerebral hemorrhage: a bibliometric analysis

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Abstract

This study aimed to analyze the scientific literature on robot-assisted interventions for intracerebral hemorrhage and related hemorrhagic stroke pathologies using bibliometric methods, in order to identify temporal publication trends, core research themes, key contributors, and the structural characteristics of the field. Original research articles published between 2000 and 2026, indexed in the Web of Science Core Collection, were analyzed. A total of 223 original articles met the inclusion criteria after systematic screening. Annual publication output remained low between 2000 and 2015, followed by a sustained increase after 2016, with a historic peak of 40 articles reached in 2025. The highest average citations per article occurred in 2015 (57.00 citations), reflecting the impact of seminal clinical validations during that period. Neurosurgical Review and Journal of Neurosurgery were identified as the most productive journals, while the United States and China emerged as the leading contributors to global scientific output, with distinct collaboration patterns. Keyword and network analyses revealed that the conceptual framework of the field is organized around core themes such as stroke, robotic technology, and rehabilitation, with a clear evolutionary shift toward functional outcomes, clinical safety, and long-term neurological recovery. Overall, the literature on robot-assisted intracranial hemorrhage management represents a rapidly maturing and expanding research domain. These findings provide a quantitative overview of the field's current structure and offer guidance for future clinical and methodological investigations.

Introduction

Intracerebral hemorrhage (ICH) is a type of bleeding within the brain tissue due to the spontaneous bursting of cerebral blood vessels(1). ICH continues to be one of the most severe forms of stroke, characterized by an approximate 30-day mortality rate of 40% and significant long-term disability among those who survive(2). Despite recent advancements in therapeutic approaches, no treatment has yet shown a significant enhancement in the functional outcomes of patients(3). In theory, surgical intervention has the potential to decrease hematoma volume and mitigate perihematomal edema in comparison to conservative management(4). Nevertheless, for the majority of patients experiencing supratentorial ICH, the efficacy of craniotomy in enhancing functional outcomes or decreasing mortality rates remains inconclusive(5), primarily due to the potential collateral damage inflicted on the adjacent brain tissue. Robot-assisted neurosurgery, as a significant advancement in minimally invasive surgery, has demonstrated remarkable advantages in the treatment of ICH.

In recent years, the rapid advancement of artificial intelligence (AI) technology has significantly propelled research and application of surgical robots. The integration of AI in medical robotics is ushering medicine into a new era. Robot-assisted neurosurgery is a safe and effective approach for intracranial hemorrhage, demonstrating superiority over conventional surgery or conservative treatment in terms of rebleeding rate, intracranial infection rate, and neurological function improvement(6). A study demonstrated that, in comparison to traditional manual puncture, stereotactic robot-guided puncture for hematoma drainage results in a reduced operative time, minimized tissue damage, a decreased

inflammatory response, enhanced hematoma clearance efficiency, and improved neurological recovery(7). In recent years, there has been an exponential increase in research literature concerning robot-assisted surgery for ICH, accompanied by a diversification of surgical techniques. Numerous bibliometric studies have systematically identified research hotspots, trends, and key contributors in robot-assisted interventions(8–11). To our knowledge, no comprehensive bibliometric or visualization analysis has been conducted to specifically examine the application of robot-assisted surgery in the context of ICH. By analyzing the extant literature, we can enhance our understanding of the potential benefits and challenges associated with robot-assisted surgical interventions for ICH.

Therefore, this study aims to comprehensively collect articles related to robot-assisted interventions for ICH published from 2000 to 2026, summarize and visualize the results, identify changes in research hotspots, and assess countries, institutions, journals, and authors with significant contributions, as well as to discover high-quality journals in the field. By conducting the inaugural bibliometric and visualization examination of published research findings pertaining to robot-assisted ICH management, we seek to synthesize prior scholarly investigations and offer a perspective on forthcoming research directions within this domain. Our work will help subsequent researchers quickly learn the current research status in the field, guide researchers toward external academic exchanges and research collaborations, and ultimately accelerate the translation of robot-assisted neurosurgical innovations into clinical applications for improved evacuation, reduced complications, and enhanced neurological recovery in patients with ICH.

Methods

2.1 Systematic Search Strategy

In this analysis, a search was performed on April 18, 2026, in the Web of Science Core Collection (WoSCC) database, covering the period from 2000 to 2026. The search strategy was constructed as follows: “(TS=((intracerebral hemorrhage* OR cerebral hemorrhage* OR brain hemorrhage* OR intracranial hemorrhage* OR hemorrhagic stroke* OR intracerebral hematoma* OR subarachnoid hemorrhage* OR intraventricular hemorrhage* OR basal ganglia hemorrhage*) AND (robot* OR robotic* OR ROSA OR Neuromate OR automated stereotactic OR robotic arm)))”. The inclusion criteria were defined as prospective, retrospective, or cross-sectional study designs. The exclusion criteria were: (1) opinion pieces, editorials, conference reports, and surveys; (2) non-English articles.

2.2 Study Selection and Data Extraction

Two independent reviewers screened the titles and abstracts of the records. Studies that did not meet the inclusion criteria were excluded. Inter-rater agreement was assessed using Cohen’s kappa coefficient, which was calculated as 0.776, indicating good agreement(12). In cases of disagreement between reviewers regarding the final selection of certain articles, a third reviewer was consulted for adjudication.

2.3 Data Processing and Visualization Analysis

Bibliometric visualization networks were created using VOSviewer version 1.6.20.0 (Leiden University, The Netherlands). This software enables the visualization of relationships among different entities such as publications, keywords, institutions, and researchers, thereby facilitating co-authorship, bibliographic coupling, and co-citation analyses(13). It was used to analyze and visualize co-occurrence networks of keywords, journals, authors, countries, and collaborations.

To further complement and refine the analysis of overall publication distribution characteristics and evolutionary patterns, this study additionally employed the bibliometrix package based on the R environment. This tool was primarily used to extract global descriptive statistics of the literature collection, including annual publication trends, contributions of core author groups, and dynamic trajectories of highly cited publications(14). By invoking its built-in biblioshiny graphical interface, a country collaboration map was constructed, enabling a more systematic macro-level characterization of the underlying structural changes within the specific research theme.

2.4 Data Analysis and Indicators

Most results of this study are presented as percentages, numbers, and graphical network maps. CiteSpace was used to perform basic literature analysis, clustering, and burst detection to identify recurring terms. Network analysis (journals and references), contribution and collaboration networks (countries), and keyword clustering analysis were applied. Three metrics were used to evaluate the quality of the output: silhouette coefficient, modularity, and centrality. Centrality assesses the importance of a node by calculating the shortest paths between every pair of nodes in the network, particularly identifying nodes that act as bridges or occupy central positions within clusters. By clustering strongly related nodes together, keyword clustering highlights relevant themes and their evolution over time. Modularity, or the Q-value, ranges from 0 to 1 and is used to determine the quality of cluster division within a network; networks with a Q-value exceeding 0.3 are considered well-structured. Finally, the silhouette coefficient (S-score) was used to assess the quality of clustering results, with values ranging from -1 to +1. An S-score greater than 0.3, 0.5, or 0.7 indicates good, satisfactory, or highly reliable network homogeneity, respectively.

Results

The search strategy retrieved 251 records from the WoSCC database. After duplicate removal and cleaning, a total of 223 articles met the inclusion criteria and were included in the bibliometric analysis (Fig. 1).

3.1 Overall Research Trends

The evolution of annual scientific output exhibited a multi-phase growth pattern during the observation period (Fig. 2a). Between 2000 and 2015, the number of publications per year remained at a low

baseline, fluctuating mainly between zero and five, reflecting the early stage of technical exploration and feasibility verification of robotic systems in hemorrhagic stroke and related pathologies. After 2016, research output showed a sustained upward momentum, reaching a periodic breakthrough of 15 publications in 2019. Thereafter, publication volume entered a phase of rapid expansion, steadily rising from 21 articles in 2021 to 30 in 2022, and reaching an all-time peak of 40 articles in 2025. The data for 2026, showing 12 articles, represent an incomplete annual count due to the current temporal coverage. This pronounced exponential growth reflects the technical maturation and clinical dissemination of automated stereotactic and robotic arm techniques in minimally invasive neurosurgical interventions for ICH(15).

Temporal distribution of scientific impact, assessed by average citations per year, revealed specific time points of high academic influence in the field (Fig. 2b). The highest citation density occurred in 2015, with an average of 57.00 citations per article. This extreme peak typically corresponds to the publication of a groundbreaking clinical trial or authoritative guideline, establishing a solid theoretical and practical foundation for subsequent research. Secondary citation peaks appeared in 2018 (43.00 citations), 2012 (33.00), and 2014 (31.00). These high-impact periods are closely aligned with the validation of the minimally invasive robotic surgery concept and the iterative cycles of technical refinement. After 2020, despite a sharp increase in total publication volume, the average citations per article gradually declined and stabilized between 15.00 and 24.00. The decrease in recent years reflects the objective time lag required for newly published articles to accumulate citations, while the large volume of publications also statistically dilutes the average citation weight per article.

To elucidate the pathways of scientific knowledge dissemination and the clustering patterns of academic resources, a three-field plot was constructed to map the topological relationships among core publications, active researchers, and research institutions (Fig. 2c). On the source-journal side, traditional neurosurgical authoritative journals such as *Acta Neurochirurgica*, *Stereotactic and Functional Neurosurgery*, and *Journal of Neurosurgery* constituted the primary vehicles for high-impact research dissemination in the field. Additionally, *Neurosurgery*, *World Neurosurgery*, and *Stroke* also accounted for substantial data flows, indicating that the research theme spans a broad spectrum from surgical techniques to comprehensive stroke management. On the researcher side, scholars such as Lee CC, Pallud J, Zanello M, and Roux A exhibited high link density, underscoring their central roles in promoting academic consensus and facilitating multi-center collaborations(16–19). On the institution side, major academic institutions such as Université Paris Cité, Goethe University Frankfurt, and Taipei Medical University absorbed the largest proportion of research output, establishing their leading position in the global robotic neurosurgery arena. The complex flow network across these three dimensions reveals a highly synergistic research ecosystem, where specialized journals effectively connect leading clinical centers with core researchers, collectively accelerating the clinical translation of robotic techniques in the management of complex intracranial hemorrhage.

3.2 Overview of Publishing Journals and Highly Cited Articles

Regarding journal distribution and temporal dynamics, the platforms for disseminating research outputs exhibited a high degree of specialization (Fig. 3a and b). Neurosurgical Review and Journal of Neurosurgery were the most core source journals in the field, leading in the number of publications. The cumulative publication curves over time show that early research was sporadic, with a relatively slow overall growth trend. After 2017, the slopes of the cumulative curves for major journals began to rise collectively, with accelerated expansion after 2020. This explosive growth is evident not only in traditional core neurosurgical journals but also in interdisciplinary journals such as the Asian Journal of Surgery and the Journal of Neuroengineering and Rehabilitation. This multi-point growth trajectory reflects that automated stereotactic and robotic arm techniques have moved beyond basic theoretical validation and are now deeply penetrating into neuroengineering optimization, rehabilitation medicine, and broader clinical surgical practice(20).

The Reference Publication Year Spectroscopy (RPYS) provided deep insight into the historical evolution and theoretical accumulation of the knowledge base in the field (Fig. 3c). Both the raw citation count and the deviation from the 5-year median highlighted key academic breakthroughs at specific historical nodes. The RPYS graph shows that reference publication years underwent a steady accumulation period before 2010, followed by a steep upward trend. Between 2015 and 2020, both absolute citation counts and relative deviation displayed dense and pronounced extreme peaks. This indicates that current research is highly dependent on literature published in the last decade, which now constitutes the most essential technical reference and theoretical cornerstone for contemporary robot-assisted neurosurgery. This high frequency of citations to recent literature fully aligns with the objective development pattern of rapid technological iteration and compact clinical translation cycles in the fields of medical AI and high-end medical devices.

The distribution of the most globally cited documents further confirmed the cross-disciplinary knowledge absorption capacity of this research direction (Fig. 3d). The top-cited articles originated from diverse academic backgrounds. The study by Gill IS et al., published in European Urology in 2011(21), received the highest number of citations, indicating that the systematic standards and safety evaluation models established during the early exploration of robot-assisted surgery in fields such as urology provided an important paradigm and underlying logic for the introduction of robotic techniques in neurosurgery. Meanwhile, studies by Serletis D et al. (2014 in Journal of Neurosurgery) (22) and Gopesh T et al. (2021 in Science Robotics)(23) established authoritative consensus within specialized applications. The sources of these high-impact articles extend beyond pure neurosurgery to biomedical engineering, general surgery, and basic neuroscience, confirming that robot-assisted intervention for ICH is a complex, cutting-edge topic that integrates mechanical dynamics, spatial navigation planning, and precision clinical surgery.

3.3 Author Analysis

The visualization network based on author co-occurrence revealed the topological structure of micro-level scientific communities and the distribution of research forces in the field (Fig. 4a). The overall network exhibited significant modularity and decentralization, forming several clearly delineated

and relatively isolated research clusters. This spatial distribution pattern suggests that current technical development and clinical translation of robot-assisted intracranial hemorrhage intervention mainly rely on in-depth exploration within specific institutions, while broad cross-team collaborative networks are still developing. Among the core subnetworks, clusters centered around Chen Yue and Cleary Kevin, around Zanello Marc and Pallud Johan, and around Tang Zhouping and Chen Shiling displayed the strongest local cohesion and highest academic output density. The dense links between nodes reflect stable knowledge-sharing channels and collaborative coherence within these high-output clusters; such highly integrated team collaboration models are key organizational guarantees for overcoming the dual barriers of developing high-end medical equipment and performing complex minimally invasive neurosurgical procedures.

The overlay visualization based on average publication year precisely mapped the temporal evolution trajectories and dynamic changes in research activity of core scientific forces in the field (Fig. 4b). The map intuitively reflects generational transitions among knowledge producers. Scholar nodes colored in dark blue to violet were mainly active between 2018 and 2020; these early exploration teams completed the initial concept validation and feasibility assessment of robotic techniques in hemorrhagic neurosurgical intervention. Green-toned clusters represent the mid-range research forces active around 2021, marking a steady amplification of research scale and gradual refinement of technical approaches. The most recent dynamic academic arrays are composed of bright yellow nodes, including the clusters of Chen Yue, Yang Huai-che, and Cebula Helene, whose main output was concentrated between 2023 and 2024. These highly active research clusters at the forefront of the timeline represent the current vanguard of scientific research, indicating that the research focus of this interdisciplinary field is accelerating toward functional iteration of robotic systems, intelligent image-guided navigation planning, and large-scale multi-center clinical validation of efficacy.

3.4 Country Analysis

Based on country collaboration mapping and corresponding author data, the global research landscape in robot-assisted intracranial hemorrhage intervention exhibited significant uneven agglomeration (Fig. 5a). The United States and China occupied the absolute leading positions in cumulative publication output, forming a dual-core array of global academic production. Not only did these two countries dominate total publication numbers, but their node intensity and link density on the global collaboration map also confirmed their status as major sources of knowledge innovation. Germany, Canada, and France followed closely, forming a second tier with strong academic radiation capacity, reflecting that North America, East Asia, and Western Europe are the most active geographic blocks for technical development and clinical application of this interdisciplinary field.

Quantitative analysis of the ratio of single-country publications (SCP) to multiple-country publications (MCP) clearly delineated the research organization models and international collaboration dependency of major producing countries (Fig. 5b). Although the United States and China ranked first in absolute numbers of MCPs, SCPs accounted for the vast majority of their total output structures, reflecting that both countries possess highly complete domestic research and development industrial chains and

abundant endogenous scientific resources, enabling strong independent technical capabilities. In contrast, countries such as Germany, Canada, and France exhibited a significantly higher relative proportion of MCPs, indicating a highly outward-oriented research ecology deeply reliant on the re-organization and complementary advantages of international academic resources. Additionally, outputs from Japan, South Korea, and Turkey were highly concentrated on domestic independent research, showing a more closed, internal translation characteristic.

The country co-authorship network topology further revealed the micro-level collaborative structure of the global scientific community (Fig. 5c). The entire collaboration network centered mainly on the United States and China as gravitational hubs, generating multiple secondary clusters with regional geographic attributes. The US node exhibited very high centrality, maintaining extensive direct research collaborations with India, South Korea, and several European countries. The China node established deep links with core European research forces such as the United Kingdom and Italy. Moreover, Canada, Switzerland, and some Asian countries formed another subnet with specific collaborative depth. This multi-polar network structure suggests that cross-border technical exchange and multi-center clinical data mutual recognition have become core driving mechanisms for the standardization and broad deployment of complex medical equipment in the field.

3.5 Keyword Analysis

Based on a two-dimensional topological analysis combining keyword co-occurrence networks and thematic evolution maps, the knowledge architecture of the field of robot-assisted intracranial hemorrhage intervention exhibited clear modular distribution and hierarchical evolutionary characteristics. On the thematic map, situated in the two-dimensional space of centrality and density, stroke, robotics, and rehabilitation constituted the core driving engines of the field (Fig. 6a). These three core concepts, located in the upper-right quadrant, exhibited both high centrality and high density, indicating that their internal theoretical systems have reached a high level of maturity and dominate the overall research network. Basic-theme concepts located in the lower-right quadrant included hemorrhagic pathology, safety, efficacy assessment, comprehensive management of ICH, and clinical trials. These themes possess strong centripetal force but relatively limited internal development density, reflecting that they serve as fundamental support connecting the entire macro research field and constitute validation steps that any new technology must undergo before clinical application; nonetheless, large-scale cohort studies are still needed for deeper exploration of specific technical nuances. Niche themes in the upper-left quadrant, such as stereotactic radiosurgery, CyberKnife, and time-window management of subarachnoid hemorrhage with hydrocephalus, represented highly specialized areas with well-developed internal technical threads but relatively weak cross-linkage with other branches from a global perspective.

The topological co-occurrence network of keywords further deconstructed the micro-level clustering patterns of the above-mentioned macro themes. The entire semantic network was clearly divided into several tightly interlocked core modules with distinct functions (Fig. 6b). The red cluster array, with ICH

and its clinical management as hub nodes, was deeply associated with minimally invasive evacuation, hematoma drainage, prognostic factors, and multi-center trials, fully depicting the standardized exploration pathway for acute-stage surgical intervention(24, 25). The green and yellow cluster matrices jointly focused on operational precision and multi-dimensional risk control in minimally invasive surgery; through dense connections of high-frequency terms such as stereotactic techniques, frameless navigation, biopsy accuracy, and high-resolution magnetic resonance imaging, they characterized the underlying logic of robotic systems in improving deep-lesion targeting accuracy and reducing postoperative complication rates(26, 27). The blue cluster module extended independently into the functional reconstruction phase after neurological injury, closely centered on motor performance recovery and balance/gait training, highlighting the key interventional role of rehabilitation robotics in improving long-term neurological outcomes for patients with moderate to severe stroke(28, 29). This networked knowledge topology—from point to surface, from acute-stage minimally invasive physical evacuation to targeted long-term rehabilitation of injured neurological functions—completely maps the full-cycle clinical application scenarios and technological iteration directions of this interdisciplinary field.

Discussion

This study systematically analyzed the dynamic evolution of annual output, academic influence, journal distribution, research entities, and research hotspots in the field of ICH intervention using bibliometric methods. The following discussion integrates the findings with the current clinical application status of relevant technologies to clarify the field's development context and future trends.

The annual publications in the field demonstrated a multi-stage growth pattern (initial exploration from 2000 to 2015, steady growth from 2016 to 2019, rapid expansion after 2021). This growth was driven by breakthroughs in robotic technology and the clinical demand for minimally invasive ICH intervention. The incomplete data for 2026 is unrepresentative.

The temporal distribution of academic influence identified key nodes (the highest average citations in 2015, secondary peaks in 2012, 2014, and 2018). The decline in average citations after 2020 was due to the citation time lag and the surge in publication volume rather than a reduction in research quality.

The field's academic dissemination primarily relies on authoritative neurosurgical journals. Interdisciplinary journals are showing a growing number of publications, which reflects the expansion of robotic technology into related fields. The knowledge base is highly reliant on literature published in the past decade. Intensive citation peaks between 2015 and 2020 have formed the core theoretical and technological system. Globally highly cited literature from various disciplines confirms the field's ability to absorb interdisciplinary knowledge.

The academic community exhibits a modular and decentralized structure, featuring relatively isolated research clusters. Meanwhile, core clusters led by key scholars offer effective collaboration models. Core research forces have experienced generational replacement, with the focus shifting from technical

feasibility to precision optimization and clinical verification. Globally, the U.S. and China serve as the dual cores of research output, boasting strong independent research capabilities and forming an unbalanced agglomeration pattern. Cross-border collaboration has become a core driving force for the development of the field.

Keyword analysis reveals that the field's knowledge structure exhibits distinct modular and hierarchical characteristics. With stroke, robotic technology, and rehabilitation treatment as the core drivers, basic themes offer necessary verification support, and edge themes represent specialized directions. The three core modules of the keyword co-occurrence network form a closed loop, mapping the full-cycle clinical application scenarios and technological iteration directions of robot-assisted ICH intervention.

This study is limited by database coverage, incomplete 2026 data, and a lack of in-depth analysis of the internal quality of the literature. Future research should focus on strengthening cross-border and cross-institutional collaboration, optimizing core technologies, expanding large-scale cohort studies, deepening interdisciplinary integration, and promoting the global popularization of robotic technology to advance the field's development.

Declarations

Competing interests

The authors declare no competing interests.

Ethics approval

This study is a bibliometric analysis based on publicly available data and does not involve human participants or animals. Therefore, ethics approval was not required.

Consent to participate

Not applicable.

Consent to publish

Not applicable.

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Author Contribution

Author Contributions Conceptualization, Alimasi abulizi.; Methodology, Alimasiabulizi and S.Y.; Formal Analysis, Alimasi abulizi and S.Y.; Writing-Original Draft, Alimasi abulizi and Aximujiang Axier; Visualization, Aximujiang AxierSupervision, Z.W. and X.L.

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Figures

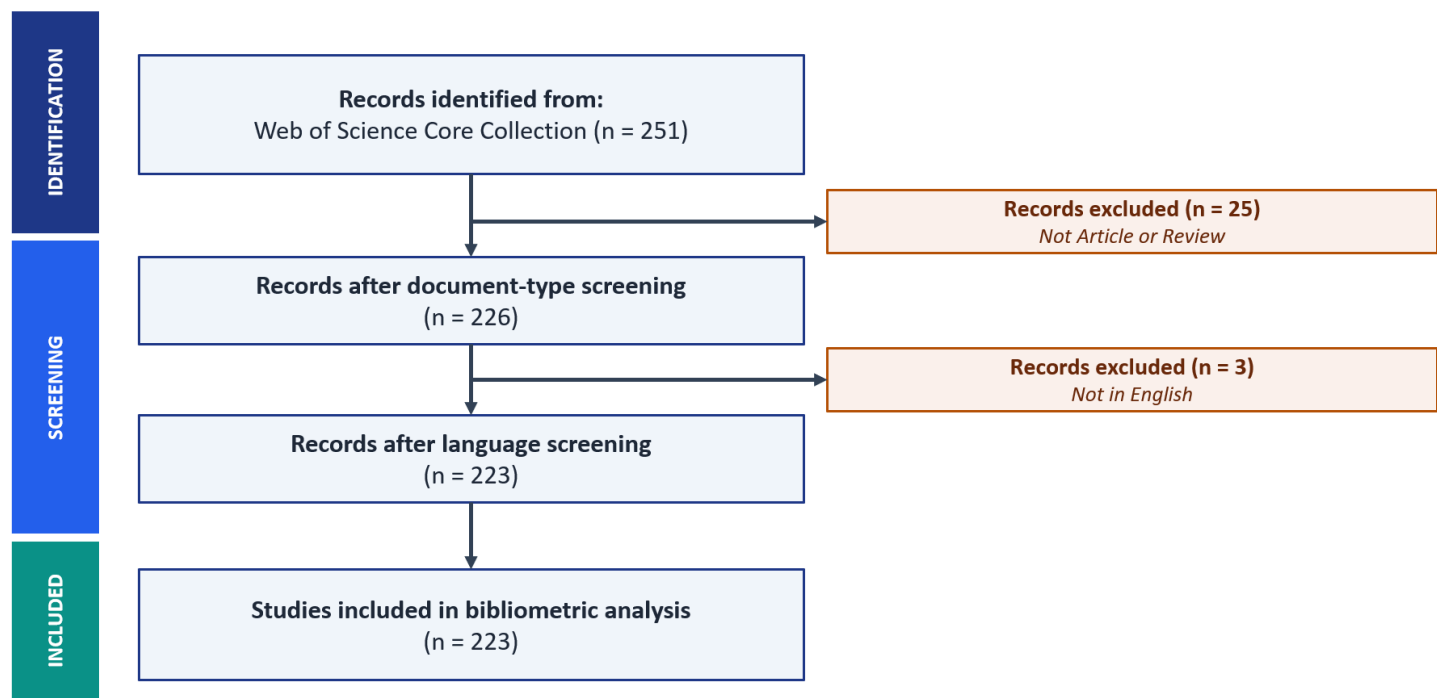


Figure 1

Flow diagram of the study selection process

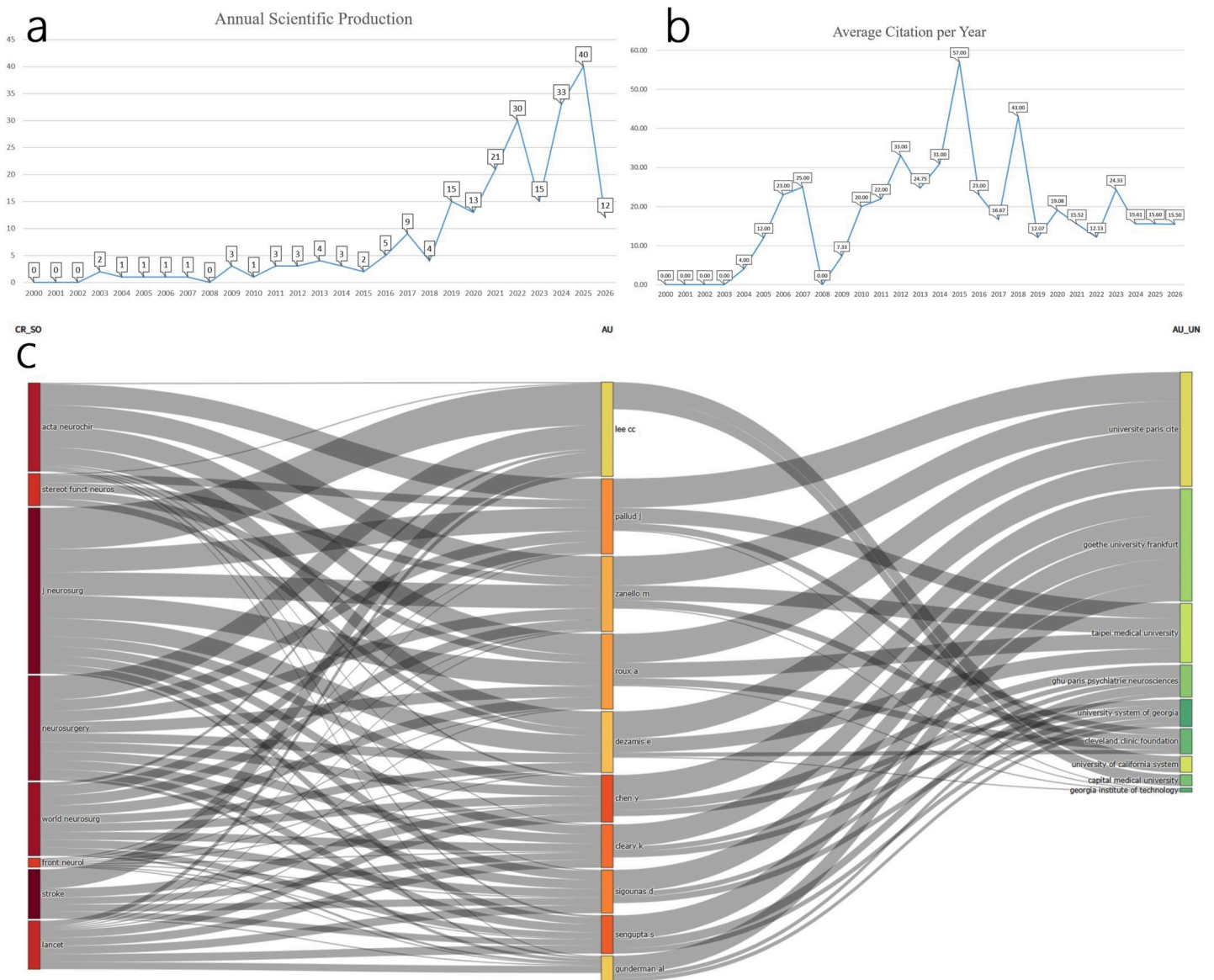


Figure 2

a Annual scientific production from 2000 to 2026.

b Average citations per year from 2000 to 2026.

c Three-field plot showing relationships among source journals, core authors, and affiliated institutions.

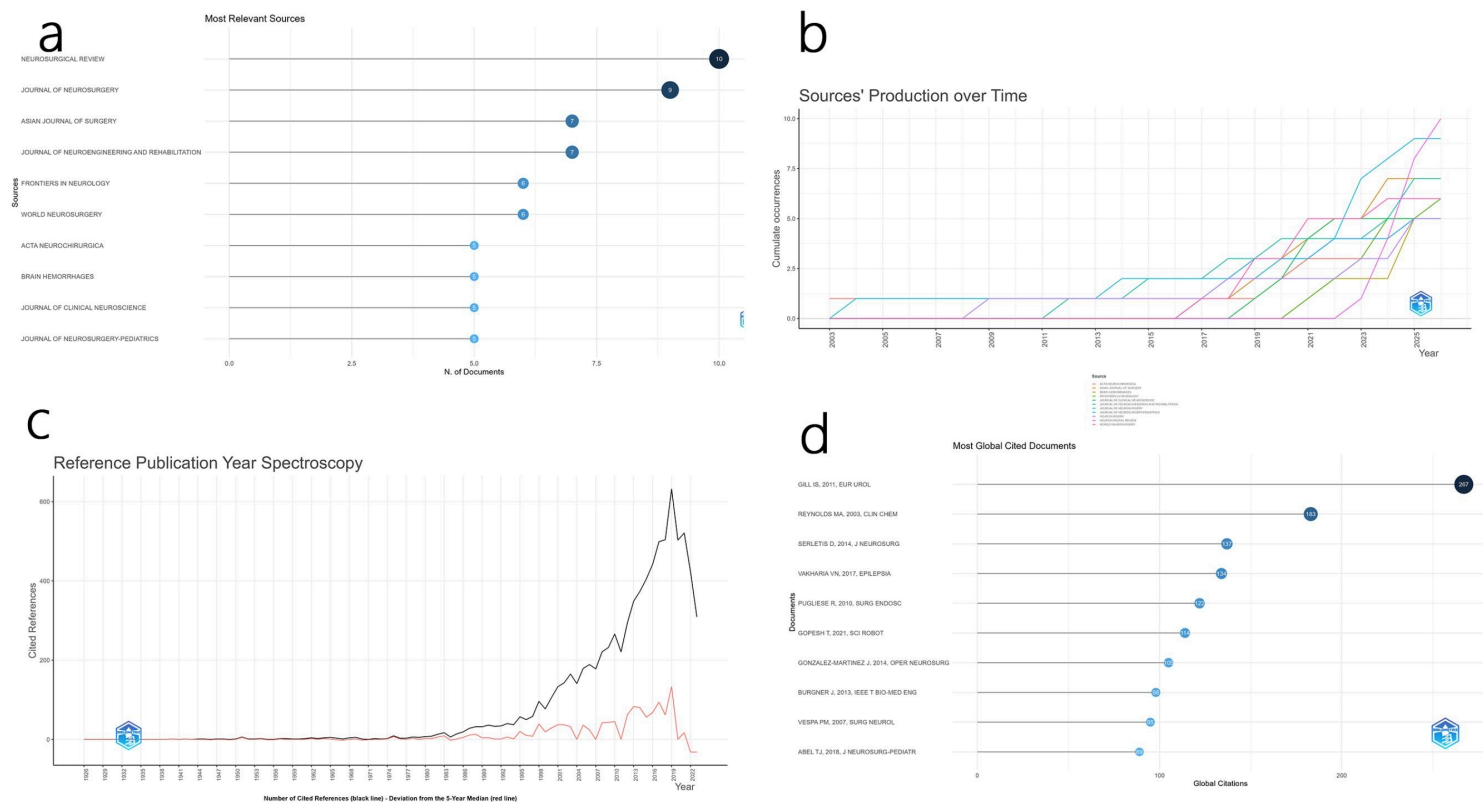


Figure 3

a Most relevant sources by number of publications.

b Sources' production over time (cumulative publication output).

c Reference Publication Year Spectroscopy (RPYS).

d Top 10 most globally cited documents.

 VOSviewer

A horizontal timeline bar with a color gradient from dark blue on the left to yellow on the right. Ticks are marked for the years 2018, 2020, 2022, and 2024.



b Overlay visualization of the author collaboration network based on average publication year.

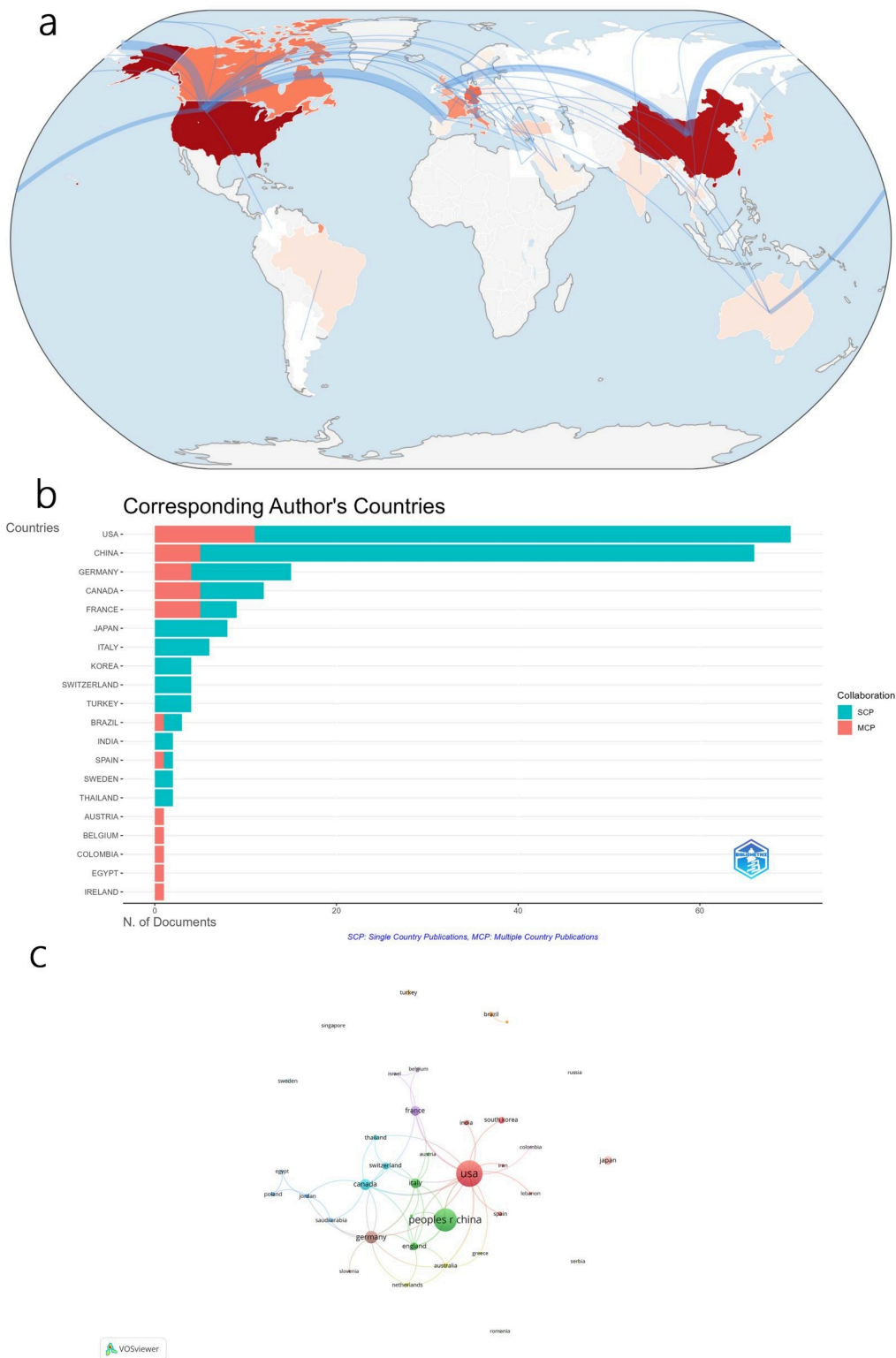


Figure 5

a International country/region collaboration map.

b Corresponding authors' countries/regions showing publication output.

c Country/region co-authorship network.

