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Article

Application of 3D printing in neurosurgical medical teaching and surgical training: Bibliometric analysis and prospects

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Abstract: Background: Traditional education in neurosurgery primarily relies on observation, giving residents and interns limited opportunities for clinical practice. However, the development of 3D printing has the potential to improve this situation. Based on bibliometrics, we analyze the application of 3D printing technology in neurosurgery medical education and surgical training. **Methods:** We searched the publications in this field in Web of Science core collection database from September 2000 to September 2023. VOS viewer, Citespace and Microsoft Office Excel were used to visually analyze and draw knowledge graphs. **Results:** A total of 231 articles and reviews were included. The United States is the country with the largest volume of articles and Mayo Clinic is the leading organization in this field. Partnership between countries, authors and institutions is also presented. World Neurosurgery is the journal with the highest number of publications. The top three key words by occurrence rate are "3D printing", "surgery" and "simulation". **Conclusions:** In recent years, more and more attention has been paid to the research in this field. According to bibliometric analysis, "accuracy" and "surgery simulation" are the research focuses in this field, while "augment reality" is the potential research target.

Keywords: 3D printing; neurosurgery; surgical simulation and training; advanced medical education; bibliometric analysis

1. Introduction

Neurosurgery is one of the most important departments in clinical medical surgery, focusing on research areas such as intracranial aneurysms, spinal diseases, intracranial tumors, craniotomy, skull fusion, nerve repair, etc. (Blohm et al., 2022). It is obvious that neurosurgery is generally more challenging, with a relatively low tolerance for surgical errors and severe consequences of surgical failure (Brazdzionis et al., 2022). Moreover, neurosurgery and related pathological structures are relatively complex and more difficult to observe directly (Li et al., 2022). In addition, some neurosurgical diseases are relatively rare and seldom encountered clinically (Graffeo et al., 2023). Ethical issues in traditional neurosurgery training are also complex and tough to deal with, which is one of the factors that cannot be ignored (Lai et al., 2022). As a result, the study of interns is primarily observation-based, providing them with limited opportunities for hands-on practice. Consequently, neurosurgical interns often lack sufficient practical experience. (Joseph et al., 2020). Therefore, neurosurgery urgently needs new training models to address this gap.

As a novel technology, 3D printing can highly restore human structures at a lower cost and has been widely used in several clinical surgical departments such as orthopedics (Shi et al., 2022) and spine surgery (Lin, Chen, et al., 2023), which achieved good results. The usage rate of 3D printed models among neurosurgery residents and medical students ranked second among surgical disciplines (14.0%), second only to otolaryngology (22%), with high evaluations for the models' comprehensive satisfaction and fidelity (Taritsa et al., 2024). For neurosurgery, on the one hand, 3D printing technology can simulate parts of the structure of human nervous system and embed these structures into the human body to replace diseased or necrotic tissues, such as 3D printing-assisted cranioplasty (Csámer et al., 2023). On the other hand, 3D printing technology can accurately replicate the structure of the human nervous system (especially the brain and cranial bones), so it can be applied in the training of neurosurgeons (Blohm et al., 2022) and neurosurgical preoperative simulation (Lan et al., 2019). What's more, it can also be used for preoperative health education to inform patients about the principles and risks of surgery (Dong et al., 2018). Due to its convenience, low cost, and high simulation capabilities, 3D printing is increasingly applied in neurosurgical education and preoperative simulation, demonstrating significant effects in reducing surgical time, minimizing complications, and improving patient prognosis (Morris et al., 2023; Ozgıray et al., 2024).

Bibliometric analysis is an emerging method for analyzing literature, which reveals the research progress and predicts the development trend of this field by systematically examining a large volume of publications in a given field, so as to statistically analyze the characteristics and trends of the papers published in this direction, including linkages by year, country/region, institution, authors, journals, keywords, citation frequency and other characteristics (Lin and Nan et al., 2022). Such analysis provides valuable information for researchers and guides in-depth research in the field (Lin and Kotheeranurak et al., 2020).

Currently, there are numerous systematic reviews on the application of 3D printing technology in the field of neurosurgical medical education (Sakaeyama et al., 2024; Taritsa et al., 2024), but there are no bibliometric analysis studies in this area. In recent years, relevant research in this field has matured. Therefore, our research aims to analyze the application of 3D printing technology in neurosurgical medical education and surgical training in real time, reveal research progress and predict the future development trends in this field. This analysis will identify current research hotspots, laying the theoretical foundation for subsequent research and providing a reference for clinical practice.

2. Method

We searched and successfully obtained 382 publications from the Web of Science Core Collection (WoSCC) database on 1 October 2023.The search formula used is: (TS = (3D OR three-dimensional)) AND (TS = (print*)) AND (TS = (neurosurgery OR neurosurgical OR skull OR intracranial OR scalp OR cerebral OR brain OR craniocerebral OR cerebrovascular)) AND (TS = (educat* OR train* OR teach* OR learning OR practice)). We selected articles and reviews, and manually screened out 231 literatures related to the application of 3D printing in neurosurgery medical education and surgical training. We downloaded the complete records of each article, including author, title, source, abstract, and cited references.

We used VOS viewer, Citespace 6.2.R4 and Microsoft Office Excel for data statistics and visual analysis. Our analysis focused on the annual number of published papers, co-occurrence and emergence of keywords, co-occurrence of countries/regions and institutions, collaboration among authors and co-cited authors, journal distribution, and cited literature distribution.

3. Results

3.1. Annual trend of publications

Since 3D printing has only gradually developed in this research field in recent years, there are relatively few articles, with only 231 published from 2000 to September 2023 (**Figure 1**). From 2001 to 2012, only two articles were published in this field. However, since 2012, attention has been paid to this research field, and the number of studies has begun to show a growing trend, and it has witnessed explosive growth after 2019. The years 2020 and 2023 have the highest number of publications, with 40 articles each.

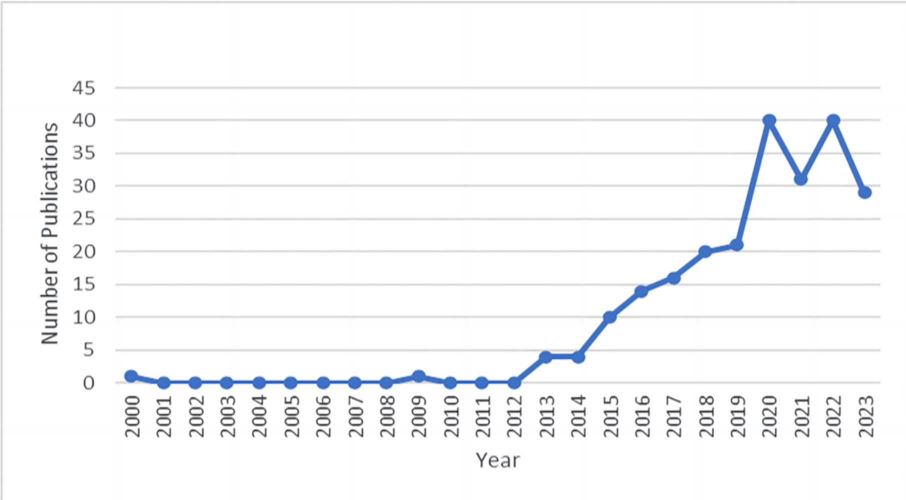

Figure 1. Year distribution of the 231 articles.

3.2. Keywords co-occurrence analysis

We used VOS viewer to extract and analyze keywords, retaining 139 keywords with a frequency of more than 10. The visual analysis of keyword clustering is shown in **Figure 2**, where different colors represent different clusters. This study is divided into 5 clusters. The larger the node label in the figure, the more frequently the keyword appears. Among the 5 clusters, there are many red and green node labels, primarily involving 3D printing technology, teaching and surgical simulation and training in neurosurgery, as well as the establishment and application of 3D printing models in the medical field.

Table 1 shows the top 20 keyword co-occurrence terms. The top three keyword co-occurrence terms are “3D printing”, “surgery”, and “simulation”. In addition, additive manufacturing, virtual reality and 3D models also appeared multiple times in different publications.

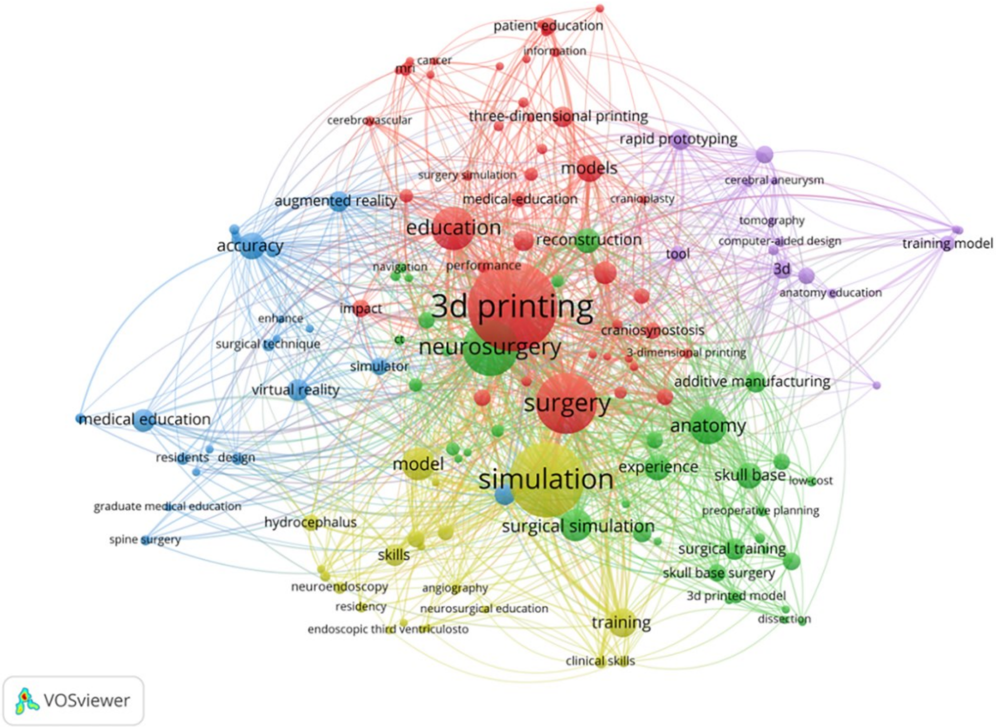

Figure 2. The co-occurrence network of keywords.

Table 1. Top 20 keywords.

Count	Centrality	Rank	Keyword	Count	Centrality
101	0.26	11	Experience	16	0.06
49	0.37	12	Skull base	15	0.16
41	0.13	13	Models	13	0.12
19	0.17	14	Additive manufacturing	11	0.08
19	0.11	15	Augmented reality	11	0.03
19	0.15	16	Reconstruction	10	0.13
17	0.2	17	Skills	9	0.13
17	0.09	18	3D model	9	0.02
17	0.04	19	Rapid prototyping	8	0.05
17	0.04	20	3D	8	0.1

Keywords burst detection can identify sudden increase in frequency within a short period, revealing changes in research hotspots over time as a reflection of the evolution trend. The analysis of keywords bursts is shown in **Figure 3**. The burst term with the highest burst intensity is “experience”, and “rapid prototyping” is the burst term with the longest duration. The burst terms in recent years are “neurosurgery education”, “surgical training”, and “training model”, indicating that the current research hotspots and trends are mainly focused on the application of 3D printing in neurosurgery teaching and surgical training, this suggests that the field has great research prospects.

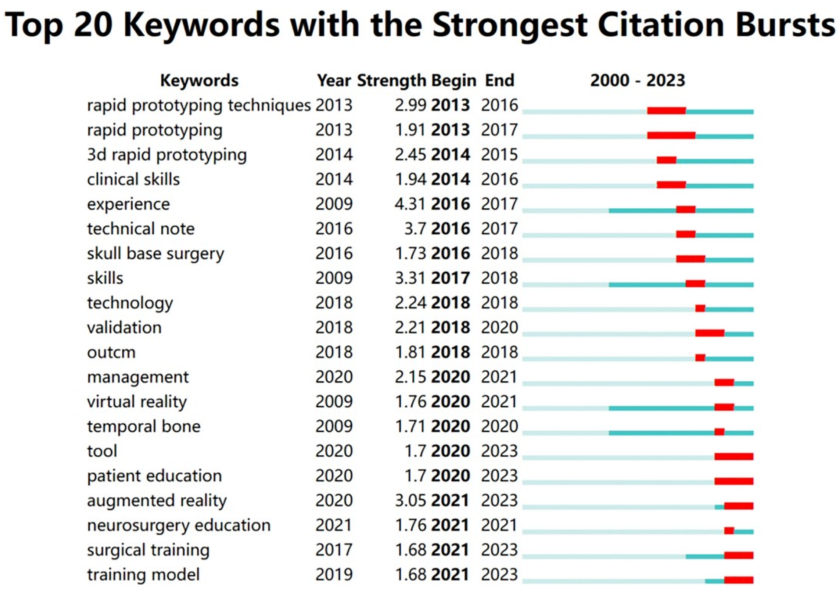

Figure 3. Top 20 keywords with the strongest citation bursts.

Note: the red bar is the burst phase.

3.3. Countries/regions co-occurrence analysis

As shown in **Figure 4**, a total of 39 countries worldwide are involved in research on 3D printing in neurosurgical medical education and surgical training (the circles represent countries/regions, and the volume of the circles indicates the number of published articles; the size of the concentric circles represents the number of articles published that year; the thickness of the lines between the circles indicates the number of collaborations, and the color indicates the year of the first collaboration), and the top 10 countries with the highest number of publications are shown in **Table 2**. The United States published the most papers (n = 88), followed by China (n = 41), with Germany and Australia tied for third place (n = 13). What's more, the largest connected components of countries/regions co-occurrence contained 39 nodes and 64

Table 2. Top 10 countries and institutions by number of publications.

Rank	Country/Region	Year	Articles	Centrality	Rank	Institution	Country/Region	Articles
1	USA	2000	88	0.51	1	Mayo Clinic	USA	10
2	China	2015	41	0.41	2	Barrow Neurological Institute	USA	6
3	Germany	2009	13	0.21	3	Chinese Academy of Medical Sciences—Peking Union Medical College	China	5
4	Australia	2015	13	0.09	4	Harvard University	USA	5
5	Canada	2013	12	0	5	Harvard Medical School	USA	5
6	England	2014	11	0.18	6	University of California System	USA	5
7	Italy	2018	10	0.07	7	Universiti Malaya	Malaysia	5
8	Japan	2013	10	0	8	Fujian Medical University	China	5
9	South Korea	2019	9	0.12	9	Peking Union Medical College	China	4
10	Spain	2015	9	0.09	10	Seoul National University Hospital	South Korea	4

connections with a map density of 0.0864. The top five countries are the United States, China, Germany, the United Kingdom, and the Dominican Republic, all of which have centrality greater than 0.1, meaning they play an important role in the field. Based on these statistical results, the United States is identified as the core country in this research area.

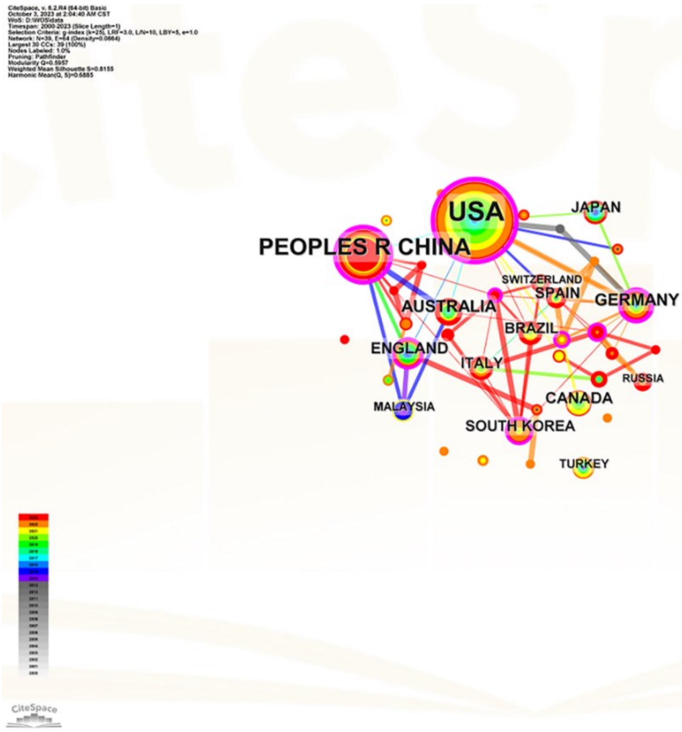

Figure 4. Visualization map of countries/regions collaboration.

3.4. Institutions co-occurrence analysis

Visualization map of institutional collaboration is shown in **Figure 5**. Over the past 23 years, a total of 212 institutions around the world have participated in the research of 3D printing in neurosurgical medical education and surgical training, with New York University being the first institution to conduct research in this field. The top 10 institutions by number of publications are shown in **Table 2**, which are from USA (5/10), China (3/10), Malaysia (1/10) and South Korea (1/10). Mayo Clinic ranked first in the number of publications (n = 10) and Barrow Neurological Institute ranked second (n = 6).

Figure 5 shows that the largest connected components of institutions co-occurrence contained 211 network nodes and 249 connections (density = 0.0112). The research institutions are primarily located in the USA and China; however, the connection density indicates that the institutions are not closely connected.

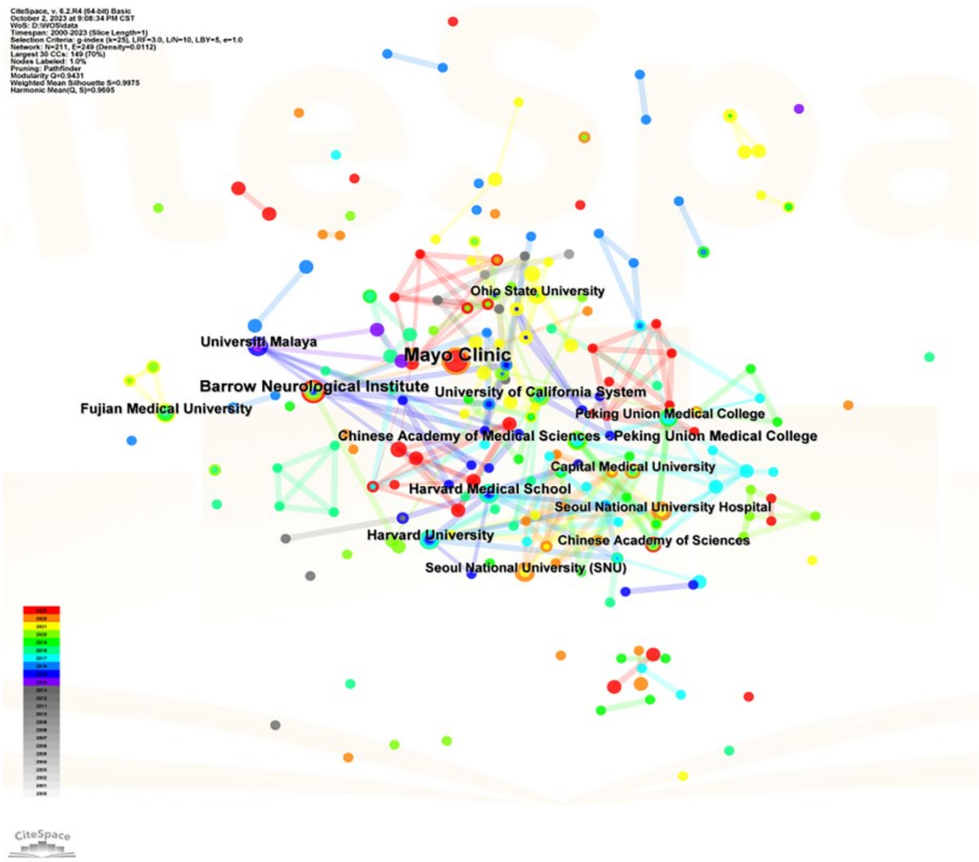

Figure 5. Visualization map of institutional collaboration.

3.5. Authors and co-cited authors analysis

As shown in **Figure 6**, the size of the nodes is proportional to the number of studies published by each author. The link color represents the year in which the article was published, and the link cluster represents the collaboration among authors. DAMON A has worked closely with Clifton W., Chen S., Nottmeier E., Dove C., Pichelmann M. and Varelo-moreno F. in this area of research.

The top 13 authors and co-cited authors are listed in **Table 3**. Waran V., Damon A. and Clifton W. ($n = 6$) are the authors with the most articles produced, while Morris J. M. and Karuppiah R. are tied for second place with 5 articles each. This data shows that there are few authors focused on this research field, and the overall output is not substantial.

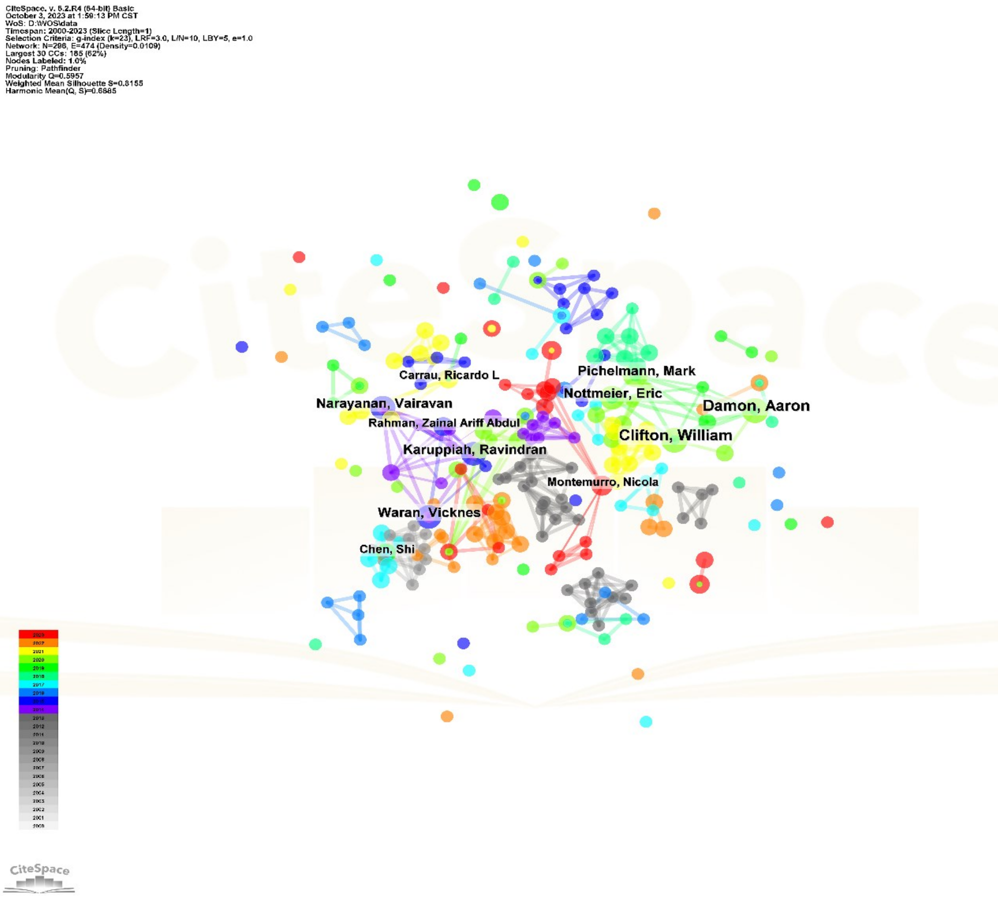

Figure 6. Visualization map of author co-occurrence.

Table 3. Top 13 authors and co-cited authors.

Rank	Author	Articles	AF	Co-Cited Author	Citation
1	Waran V.	6	0.95	Mashiko T.	52
2	Clifton W.	6	1	Waran V.	49
3	Damon A.	6	1	Ryan J. R.	39
4	Morris J. M.	5	0.78	Weinstock P.	38
5	Karuppiah R.	5	0.83	Wurm G.	36
6	Chen S.	4	0.36	Kimura T.	32
7	Pan H.	4	0.36	Ploch C. C.	29
8	Pan Z. X.	4	0.36	Tai B. L.	26
9	Yao Y.	4	0.36	[Anonymous]	26
10	Narayanan V.	4	0.58	Durso P. S.	25
11	Nottmeier E.	4	0.68	Randazzo Michael	23
12	Pichelmann M.	4	0.68	Rengier F.	20
13	Nakaji P.	4	0.68	Anderson J. R.	20

AF: Articles Fractionalized.

As shown in **Figure 7** (the circle represents the author, and the size of the circle indicates how many times that author has been cited; the size of the concentric circles in the circle represents the number of citations in the current year; the thickness of the lines between the circles indicates the number of co-citations, and the color represents the year of first co-citations), authors with higher citation frequencies have larger circles and thicker lines, indicating their recent citation frequency and co-citation frequencies. 13 authors were cited more than 20 times, with Mashiko T., Waran V., and Ryan J. R. ranking the top three. There are 8 authors with centrality ≥ 0.1, with Waran V., Rengier F., and Bernardo A. being the top three.

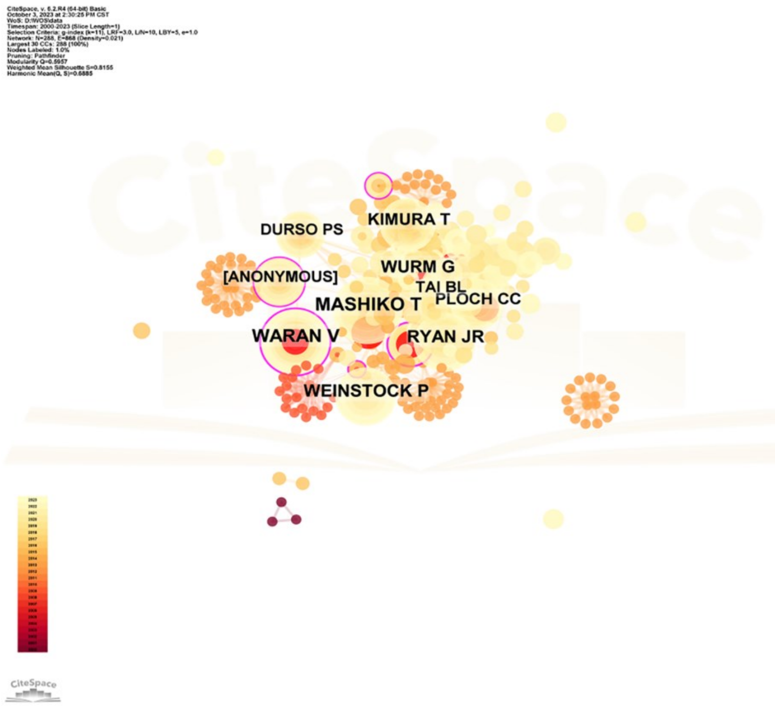

Figure 7. Visualization map of co-cited authors.

3.6. Journals distribution

We successfully accessed 105 journals through VOS viewer. The top 10 journals by the number of published articles in this research area are listed in **Table 4**. Among them, World Neurosurgery published the highest number of articles (n = 35) and the highest total citations and total link strength (858 and 122 frequency, respectively), indicating the journal's significant contribution to this field of research. Operative Neurosurgery and Cureus Journal of Medical Science tied for second place with 10 articles each, while the Journal of Neurosurgery ranked third with 9 articles.

Table 4. The top 10 journals.

Rank	Journal	Articles	Citations	Total Link Strength	IF (2022)	JCR (2022)
1	World Neurosurgery	35	858	122	1.99	Q3/Q4
2	Operative Neurosurgery	10	66	44	2.296	Q3
3	Cureus Journal of Medical Science	10	40	23	1.186	Q3
4	Journal of Neurosurgery	9	342	47	4.052	Q1/Q2
5	Journal of Neurosurgery-pediatrics	6	194	37	1.884	Q3/Q4
6	Journal of Craniofacial Surgery	6	17	4	0.901	Q4

Table 4. (*Continued*).

Rank	Journal	Articles	Citations	Total Link Strength	IF (2022)	JCR (2022)
7	Scientific Reports	5	156	27	4.562	Q2
8	Neurosurgical Focus	5	94	18	4.129	Q1/Q2
9	Childs Nervous System	5	144	25	1.445	Q4
10	Journal of Neurological Surgery Part B-Skull Base	4	26	14	0.926	Q4

3.7. Co-cited reference

The co-cited reference is shown in **Figure 8**. Among them, 12 articles have a centrality greater than or equal to 0.1, and most of the citations and co-citations occurred in the past 8 years. The top 15 cited literatures are listed in **Table 5**. Mashiko et al. (2015) "Development of three-dimensional hollow elastic model for cerebral aneurysm clipping simulation enabling rapid and low cost prototyping" had the highest citation frequency and centrality. Most of this literature focuses on the role of 3D printing in neurosurgical medical training and the establishment of relevant surgical models.

Table 5. Top 15 co-cited references.

Rank	Authors	Title	Journal	Years	Citation
1	Mashiko T.	Development of Three-Dimensional Hollow Elastic Model for Cerebral Aneurysm Clipping Simulation Enabling Rapid and Low Cost Prototyping	World Neurosurg	2015	31
2	Ryan J. R.	Cerebral Aneurysm Clipping Surgery Simulation Using Patient-Specific 3D Printing and Silicone Casting	World Neurosurg	2016	23
3	Ploch C. C.	Using 3D Printing to Create Personalized Brain Models for Neurosurgical Training and Preoperative Planning	World Neurosurg	2016	21
4	Waran V.	Utility of multimaterial 3D printers in creating models with pathological entities to enhance the training experience of neurosurgeons technical note	J Neurosurg	2014	19
5	Randazzo Michael	3D printing in neurosurgery: A systematic review	Surg Neurol Int	2016	17
6	Weinstock P.	Creation of a novel simulator for minimally invasive neurosurgery: fusion of 3D printing and special effects	J Neurosurg-Pediatr	2017	16
7	Tai B. L.	Development of a 3D-printed external ventricular drain placement simulator: technical note	J Neurosurg	2015	14
8	Vakharia V. N.	Review of 3-Dimensional Printing on Cranial Neurosurgery Simulation Training	World Neurosurg	2016	13
9	Chen S.	The role of three-dimensional printed models of skull in anatomy education: a randomized controlled trail	Sci Rep-Uk	2017	12
10	Lin J. Y.	Using Three-Dimensional Printing to Create Individualized Cranial Nerve Models for Skull Base Tumor Surgery	World Neurosurg	2018	11
11	Wang L.	Three-dimensional intracranial middle cerebral artery aneurysm models for aneurysm surgery and training	J Clin Neurosci	2018	11
12	Waran V.	Injecting Realism in Surgical Training-Initial Simulation Experience with Custom 3D Models	J Surg Educ	2014	11
13	Liew Y.	3D printing of patient-specific anatomy: A tool to improve patient consent and enhance imaging interpretation by trainees	Brit J Neurosurg	2015	10
14	Namba K.	Microcatheter Shaping for Intracranial Aneurysm Coiling Using the 3-Dimensional Printing Rapid Prototyping Technology: Preliminary Result in the First 10 Consecutive Cases	World Neurosurg	2015	10
15	Wurm G.	Cerebrovascular Biomodeling for Aneurysm Surgery: Simulation-Based Training by Means of Rapid Prototyping Technologies	Surg Innov	2011	10

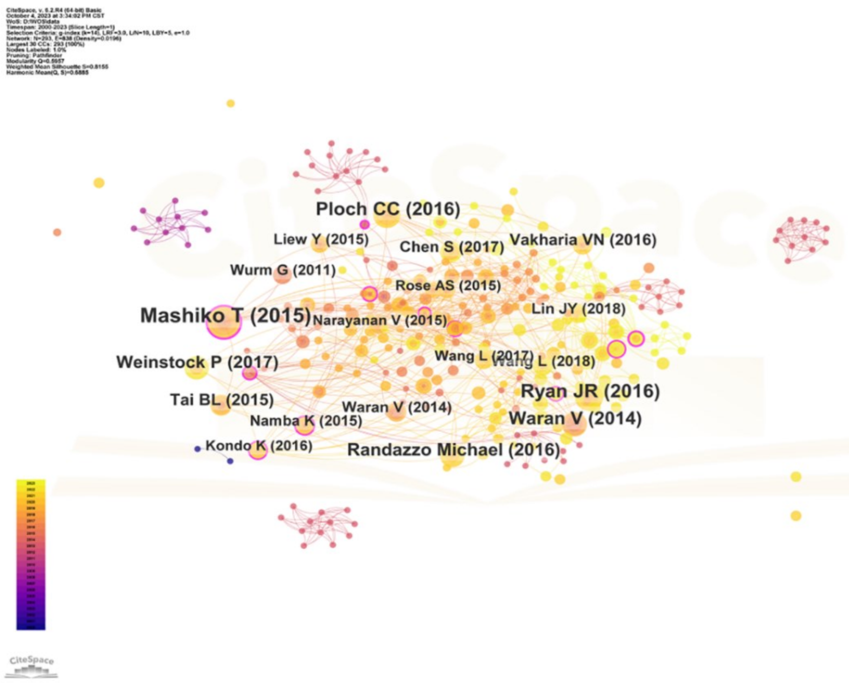

Figure 8. Visualization map of co-cited references.

We then clustered the references, as shown in **Figure 9**. Cluster #0 cerebral aneurysm had the largest number of references (41 articles), followed by cluster #1 preoperative aneurysm (39 articles) and cluster #2 patient education (37 articles). This indicates that researchers are paying close attention to the role of 3D printing in neurosurgical preoperative simulation and communication with patients. As shown in **Table 6**, the year represents the average year of the literatures cited in the cluster, which corresponds to the changes in research hotspots. The silhouette values of all 10 clusters are close to 1, which proves the reliability of the cluster.

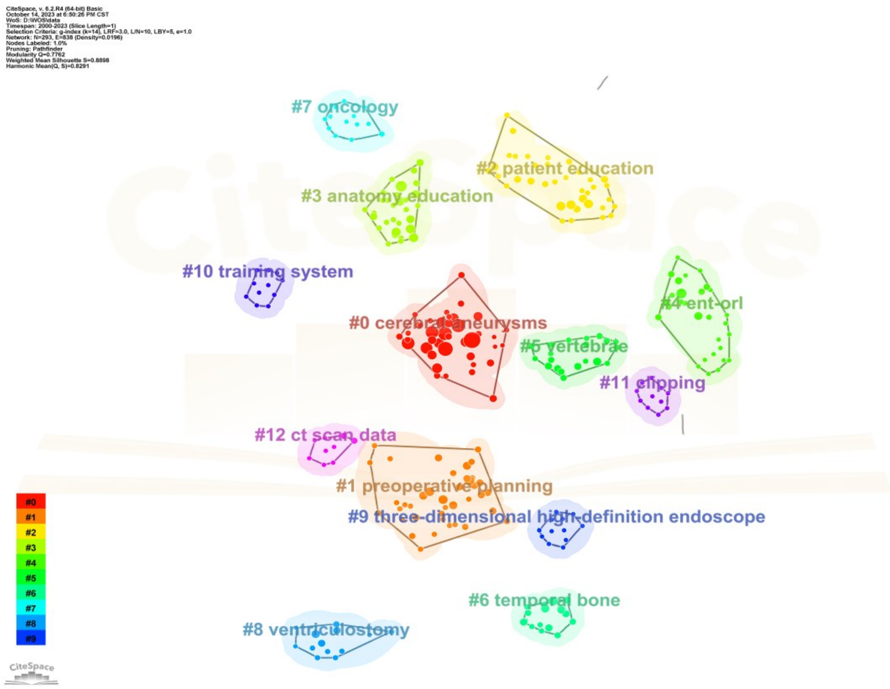

Figure 9. Visualization map of references co-citation clusters.

Table 6. Top 10 largest clusters of co-cited references.

Cluster ID	Size	Silhouette	Year	Top Terms
#0	41	0.807	2015	Cerebral aneurysms
#1	39	0.94	2018	Preoperative planning
#2	37	0.926	2019	Patient education
#3	30	0.825	2015	Anatomy education
#4	29	0.848	2011	Ent-orl
#5	20	0.918	2018	Vertebrae
#6	17	0.917	2015	Temporal bone
#7	14	0.98	2009	Oncology
#8	13	0.976	2013	Ventriculostomy
#9	12	1	2010	Three-dimensional high-definition endoscope

We also used Citespace to create a timeline to better understand the time span and development of various research topics in this area (**Figure 10**). Earlier research topics included cluster #4 ent-orl, cluster #7 oncology, and cluster #9 three-dimensional high-definition endoscope, which form the basis of this field of study. The horizontal axis represents the number of articles in each cluster, and the node size represents the frequency with which the article was cited. The fields of cluster #1 preoperative aneurysm and cluster #2 patient education have begun to develop in recent years.

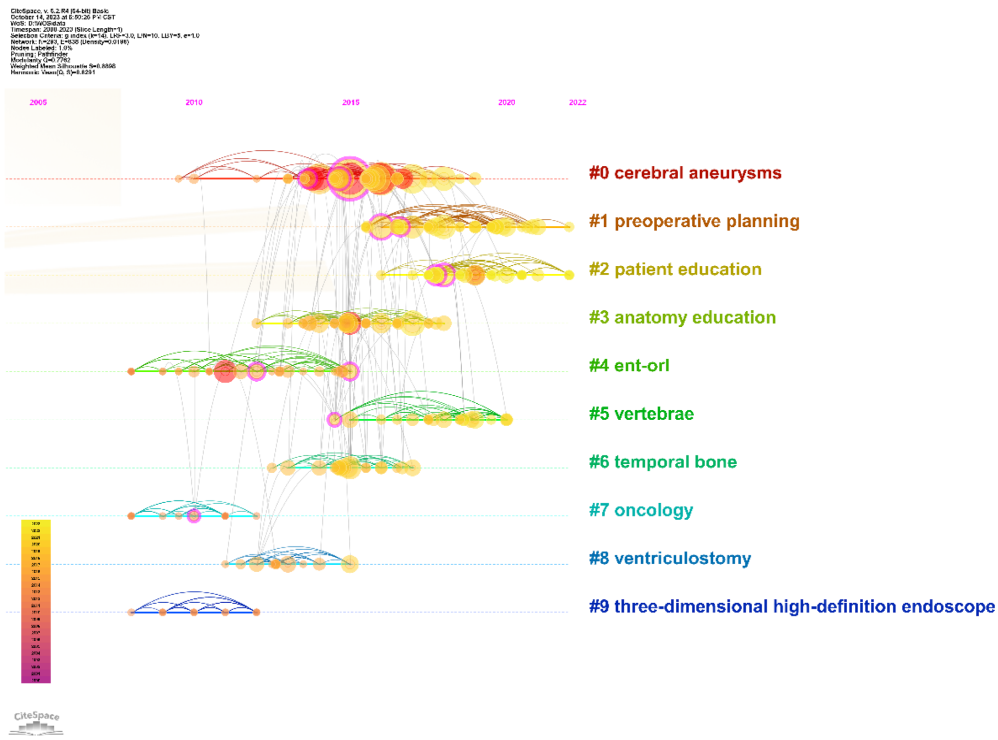

Figure 10. Timeline view of co-cited references.

4. Discussion

The nervous system is one of the most complex structures of the human body, and the brain is its most intricate organ. At the same time, the pathological changes of the nervous system are complex and diverse. These make neurosurgery a recognized high-risk department that demands a high level of expertise from clinicians. However, traditional neurosurgery teaching has great limitations. Interns typically observe and learn under the guidance of experienced doctors, with limited opportunities for hands-on practice (Clifton et al., 2020). Autopsy is an important method in neurosurgical education, but cadaver resources are scarce and expensive. Additionally, organs preserved in formalin can become deformed, preventing accurate simulation of the surgical environment, which diminishes the teaching effectiveness (Suri et al., 2016). The use of animal model is also an important educational method in neurosurgery, but the nervous systems of animals differ significantly from those of humans. Therefore, its surgical guidance is poor as well (Suri et al., 2016).

With the development of 3D printing and its increasingly extensive application in medicine, many of the aforementioned problems can be addressed. Currently, the application of 3D printing in neurosurgery education is mainly reflected in resident training, preoperative simulation and patient education (Pucci et al., 2017). It has been used in a variety of neurosurgical diseases and procedures, such as intracranial space occupying lesions, intracranial vascular diseases, cranioplasty, peripheral nerve repair and so on (Li et al., 2022). According to our research, 3D printing is also used to make medical models, medical devices and disease models. The brain structure of patients can be well reproduced by using 3D imaging techniques such as computed tomography (CT) and magnetic resonance imaging (MRI) (Ganguli et al., 2018). In resident training, the use of 3D printing technology for teaching can enhance the training experience of neurosurgeons (Waran et al., 2014) and the learning curve of residents (Lin et al., 2018). Using 3D-printed models for preoperative operation simulation helps evaluate the feasibility of operation and select the best operation plan, offering strong pertinence and specificity. This practice can also improve the success rate of operation (Lan et al., 2020), reduce operation time, and decrease the incidence of surgical complications (Martín-Noguerol et al., 2019). Furthermore, using 3D printing technology to educate patients about the surgical process and related risks can effectively reduce their anxiety and enhance informed consent (Mian et al., 2023). It also improves communication between surgeons and patients (Pucci et al., 2017).

Based on a comprehensive analysis of the results of this study, we found that publications on the application of 3D printing technology in neurosurgery teaching and surgical training showed the most significant growth in 2019. The curve of annual publication volume in the past three years is fluctuating and unstable, but this does not mean that the research field is no longer developing. From the perspective of annual cumulative publication, the number of publications in this research field shows an increasing trend. At the same time, many scholars are committed to the research in this professional field and have achieved a lot of results. All these show that there is a great research potential and significance in this field. Waran V from Malaysia ranks second in citation frequency and first in centrality, making a great contribution to the research in this field. The United States and China occupy the core positions in this research field, while some countries/regions have little research activity, indicating that the development of this research is uneven in the world and the cooperation among countries, institutions and national authors should be promoted.

We also found that "Childs Nervous System" ranked ninth in journal distribution with 144 citations, indicating that 3D printing has been widely used in pediatric neurosurgery in recent years. Compared to adults, the incidence of cerebrovascular disease in children is very low, so many neurosurgeons lack clinical experience in pediatric cerebrovascular surgery. What's more, the organs and systems of children are not fully developed, which greatly increases the difficulty of operation and clinical unpredictability. However, Christopher et al. (2023) addressed the preoperative training and medical teaching needs of neurosurgeons by developing representative 3D printed models of pediatric cerebrovascular diseases. In our analysis of the cited literature, we found that the relevant research in ent-orl appeared the earliest (2008), and over the following decades, it has extended to neurosurgery, indicating that 3D printing has a solid foundation and development potential in medicine. The continuous development of 3D printing technology has led to its increasing application in departments with more complex patient conditions.

While 3D printing is widely used in neurosurgery teaching, it still has some limitations in clinical teaching and significant room for development. First, 3D printing is expensive and time-consuming (Pucci et al., 2017). The cost of 3D printers is substantial. Data shows that using 3D printing for preoperative simulation and surgical planning costs an average of $62 per minute in the operating room (Ballard et al., 2020), and printing a skull can take up to 14 h (Naftulin et al., 2015). These high costs and long printing times limit the widespread adoption of 3D printing technology. Secondly, the accuracy and resolution of CT, MRI and other technologies hinder the further development of 3D printing technology. What's more, the radiation generated by these imaging technologies can affect the health of patients and doctors (Ganguli et al., 2018). In addition, most of the models produced by 3D printing technology are static, making it difficult to simulate the bleeding effect. Besides, the reduction of soft tissue is still not ideal (Ganguli et al., 2018).

The analysis of publication co-citation shows that the most cited article is "The Development of Three-Dimensional Hollow Elastic Model for Cerebral Aneurysm Clipping Simulation Enabling Rapid and Low Cost Prototyping" by Mashiko et al. (2015). The researchers used acrylonitrile-butadiene-styrene as the modeling material to construct a three-dimensional hollow elastic model of cerebral aneurysm, which was used in preoperative simulation and neurosurgery teaching. All actual clipping operations performed on patients who underwent preoperative simulations with this 3D printing technology were successful and consistent with the simulations. 12 surgeons gave almost universally positive evaluations of the technique post-operation, and 6 junior surgeons who had never performed the operation learned how to perform it. The second most cited article is "Cerebral aneurysm clipping surgery simulation using patient-specific 3D printing and silicone casting" by Ryan et al. (2016). The researchers used 3D printing technology and silicone casting technology to create a simulation of aneurysm clipping, which consisted of three parts: brain, skull and cerebral vessels. 14 neurosurgical residents studied using the simulator under guidance, and the form and function of the simulator were evaluated after training. The residents highly rated the clinical applicability, authenticity, and educational value of the simulations (Ryan et al., 2016). The third article cited is Using 3D Printing to Create Personalized Brain Models for Neurosurgical Training and Preoperative Planning by

Ploch et al. (2016). The researchers used 3D printing technology to create personalized brain models and explored their effectiveness. The fidelity of the models was very high, and its anatomical, physiological and mechanical properties are very similar to those of the real brains. In addition, the models were durable and deformable and the gelatin models can be reused by melting. After surveying 10 doctors, most were satisfied with the models and believed they had a wide range of uses, including patient education, physician teaching, surgical training, preoperative planning and so on. The stiffness, cutting characteristics, and tactile anatomical structure of the model can still be improved, while the anatomical structure, visual appearance and model size were considered to be very realistic (Ploch et al., 2016). The three articles are all research articles, which analyze the effects of some 3D printed models. Interestingly, all the three articles are from the journal world neurosurgery, indicating that this journal has significant value in 3D printing in neurosurgery teaching and preoperative simulation.

According to keyword analysis, the occurrence frequency and intermediary centrality of "accuracy" are among the top 10, indicating that the accuracy of 3D printing model has consistently been a research hotspot. Therefore, future research may focus on using 3D printing to create more precise models. Recently, Zongchao Yi and colleagues (2020) developed and evaluated a brain model with realistic tactile sensation and intracranial pressure for the defects of the past 3D brain model. They used it for neurosurgical training. Meanwhile, with the continuous development of 3D printing technology and material optimization, reducing the time and cost of making surgical 3D models will also become a research hotspot. In our research, the burst intensity of "augmented reality" ranks fourth (3.05), lasting from 2021 to the present, indicating that the combined use of augmented reality and 3D printing is also a research hotspot. As 3D printing becomes more popular and its positive educational effects on patients are recognized, it may be used in customized medicine in the future. This includes creating custom medical devices and implants tailored to the specific conditions of each patient, which can improve treatment effectiveness and reduce medical costs. Additionally, 3D printing may also be utilized in drug research and development: by printing out the internal organs and tissues, scientists can test the positive and negative effects of new drugs more accurately.

In our research, the application of 3D printing in neurosurgery medical education and surgical training was analyzed by bibliometrics for the first time. We discussed the related application fields, development progress, research hotspots, and possible future research targets. However, our research has some limitations. First, we only analyzed the publications from Web of Science core collection database, excluding publications from other databases, which may limit the comprehensiveness of our research. Secondly, only 231 publications meeting the criteria were selected, which is relatively small for bibliometrics study. Lastly, our study covers publications only up to September 2023, so some of the newly publications have not been included.

5. Conclusion

To sum up, our research utilized Citespace and VOS viewer to create visual maps of the application of 3D printing in neurosurgery medical education and surgical training. We comprehensively analyzed and discussed the results.

Based on the current development trend, we can forecast that 3D printing has great advantages and application potential in the field of neurosurgical medical education and surgical training. With the continuous advancement of technology and the development of new materials, 3D printing will be more widely and deeply utilized in this field in the future.

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