Current Applications of the Three-Dimensional Printing Technology in Neurosurgery: A Review

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J Neurol Surg A Cent Eur Neurosurg 2025;86:304–320.

Abstract

Background In the recent years, three-dimensional (3D) printing technology has emerged as a transformative tool, particularly in health care, offering unprecedented possibilities in neurosurgery. This review explores the diverse applications of 3D printing in neurosurgery, assessing its impact on precision, customization, surgical planning, and education.

Methods A literature review was conducted using PubMed, Web of Science, Embase, and Scopus, identifying 84 relevant articles. These were categorized into spine applications, neurovascular applications, neuro-oncology applications, neuroendoscopy applications, cranioplasty applications, and modulation/stimulation applications.

Results 3D printing applications in spine surgery showcased advancements in guide devices, prosthetics, and neurosurgical planning, with patient-specific models enhancing precision and minimizing complications. Neurovascular applications demonstrated the utility of 3D-printed guide devices in intracranial hemorrhage and enhanced surgical planning for cerebrovascular diseases. Neuro-oncology applications highlighted the role of 3D printing in guide devices for tumor surgery and improved surgical planning through realistic models. Neuroendoscopy applications emphasized the benefits of 3D-printed guide devices, anatomical models, and educational tools. Cranioplasty applications showed promising outcomes in patient-specific implants, addressing biomechanical considerations.

Discussion The integration of 3D printing into neurosurgery has significantly advanced precision, customization, and surgical planning. Challenges include standardization, material considerations, and ethical issues. Future directions involve integrating artificial intelligence, multimodal imaging fusion, biofabrication, and global collaboration.

Conclusion 3D printing has revolutionized neurosurgery, offering tailored solutions, enhanced surgical planning, and invaluable educational tools. Addressing challenges and exploring future innovations will further solidify the transformative impact of 3D printing in neurosurgical care. This review serves as a comprehensive guide for researchers, clinicians, and policymakers navigating the dynamic landscape of 3D printing in neurosurgery.

Keywords
- surgical planning
- surgical simulation
- 3D printing
- additive manufacturing
- current technological applications

received
January 20, 2024
accepted after revision
August 14, 2024
accepted manuscript online
August 16, 2024
article published online
October 16, 2024

Georg Thieme Verlag KG,
Rüdigerstraße 14,
70469 Stuttgart, Germany

DOI https://doi.org/10.1055/a-2389-5207.
ISSN 2193-6315.

Introduction

In the recent years, three-dimensional (3D) printing technology has emerged as a groundbreaking tool with immense potential in various fields, notably health care. Its impact on neurosurgery, in particular, has been revolutionary. The rapid advancements in 3D printing technology have transformed various sectors, including health care.[1–3] Specifically, neurosurgery has seen significant progress through the integration of 3D printing.

3D printing technology in neurosurgery addresses challenges such as enhancing preoperative planning through better visualization of anatomy, providing surgical training and simulation for skill development, creating patient-specific implants and instruments for improved surgical outcomes, and aiding medical education by accurately representing complex neuroanatomical structures. These advancements contribute significantly to the precision, safety, and innovation within the field of neurosurgery.[4]

3D printing, also known as additive manufacturing, is the process of creating 3D objects by adding successive layers of material based on a digital model. This technology enables the fabrication of complex structures with high precision and accuracy. The versatility of 3D printing allows for the production of customized anatomical models, implants, surgical instruments, and prosthetics tailored to meet the specific needs of patients. The 3D printing process commences with the creation of a digital model using computer-aided design (CAD) software, which serves as a blueprint for the printer to guide the deposition of materials layer by layer. Various materials, including plastics, metals, ceramics, and even biological materials, can be used for printing, depending on the desired application.

This literature review article aims to explore the current applications of 3D printing in neurosurgery, highlighting its advancements and significant contributions to patient care and surgical outcomes by reviewing the literature from medicine-oriented databases.

Methodology

For the literature review process, four databases—PubMed, Web of Science, Embase, and Scopus—were utilized to search for relevant articles. In this review, a search was conducted using MeSH terms including “3D printing,” “additive manufacturing,” “three-dimensional printing,” “neurosurgery,” and “spine surgery” to identify literature. We focused on original research studies that incorporated 3D printing within the context of neurosurgical applications, published in the English language. Given the exploratory approach of this review, stringent selection criteria were not imposed, allowing for a broader discussion of the emerging trends and applications in this field. We have selected innovative studies from various domains for this synthesis—this allowed us to provide a comprehensive review among subspecialities of neurosurgery.

Data extraction encompassed information on the country of origin, the printed device, and its applications within a specific area of interest (guiding device, prosthesis/implant, neurosurgical planning, education/training, neurosurgical robot, and other neurosurgical devices). Additionally, details were gathered on the software used for model creation, the cost (in USD), the time (in hours) required for model production, the materials used, the printing device, and the printing method.

Literature Findings

Eighty relevant articles were identified from a curated search of medical databases for this survey. Among these works, 34 were from the People’s Republic of China, 17 were from the United States, and others originated from South Korea, Australia, Japan, India, Singapore, Taiwan, Iraq, Brazil, the Netherlands, Canada, Turkey, Saudi Arabia, Switzerland, the United Kingdom, France, and Italy.

In terms of modeling software, MIMICS was the most popular, used in 35 models. Additionally, 12 works utilized 3D slicers, and 10 employed 3 Matic. A major portion of the works (48) did not specify the printing technique. The predominant methods included fused deposition modeling (FDM) in 18 works, the PolyJet technique in 12 works, and stereolithography (SLA) in 10 works. Regarding the applications of printed devices, the majority of models (49) were utilized for neurosurgical planning, 26 as guiding devices, 27 as prostheses or implants, and 14 for education or training.

Included works were categorized into ►**Table 1** based on their topics, resulting in the creation of six sections: spine applications, neurovascular applications, neuro-oncology applications, neuroendoscopy applications, and cranioplasty applications, along with modulation and stimulation applications. It is noteworthy that some works fell into two or more categories.

Spine Applications

Guiding Devices

3D-printed guiding devices are transforming spine surgery by offering precision, customization, and enhanced surgical planning.[5–29] These patient-specific tools prove especially valuable in complex spinal procedures and minimally invasive surgeries, playing a crucial role in modern spine surgery. They facilitate smooth screw placement, precise insertions, and optimal injection site identification during operations.[5,7,11,14,15,21,22,24,27,30,31]

The implementation of printed devices holds the potential to revolutionize pediatric spine neurosurgery. Willemsen et al[5] demonstrated this by creating drill guides for congenital scoliosis and basilar impression surgeries with such accuracy that they could be used for inserting cervical pedicle screws in very young children (4 years old). Unilateral placement of cervical vertebrae pedicle screws was uneventful and swift (<10 minutes per screw). Follow-ups over 9 to 36 months, involving three operations, revealed no signs of failure.

In the context of scoliosis surgeries, models play a crucial role in enhancing the accuracy of screw insertion. Ding et al[11]

Table 1 Summary of study findings for the review

Study		Printed device	Software	Time/cost	Material	Printer	Method	Use
Spine	Willemsen et al[5]	Guide drill	MIMICS, 3 Matic	N/A	Nylon powder	P110 EOS Krailling	SLS	GD
		Spinal column prosthesis			Titanium alloy	DMP 320 3D Systems	DMP	P
	Du et al[6]	Craniovertebral model	MIMICS	5–7 h/N/A	Starch/cellulose powder, urethane	Spectrum Z510	IP	NP
	Thayaparan et al[7]	Occipitocervical implant	Anatomics3D	N/A	Titanium alloy	Renishaw AM25	SLM	NP
		Drill guide			Nylon	EOSINT EOS	SLS	GD
	Faraj et al[8]	Vertebrae model	3D Slicer	N/A	N/A	Da Vinci XYZ	N/A	NP
	Goel et al[9]	Craniovertebral model	Vizua	5h/$350	N/A	Projet 660 3D Systems	CJP	NP
	Mobbs et al[10]	Vertebral implant	3D Morphic	N/A	Titanium alloy	EOSM100 Krailling	SLM	P
	Ding et al[11]	Pedicle screw insertion guide	MIMICS	N/A	Resin	N/A	N/A	GD
		Spine model			Resin	N/A	N/A	NP
		Osteotomy guide	ProE		Resin	N/A	N/A	GD
	Rutkowski et al[12]	Spine model for scoliosis surgery	MIMICS, 3 Matic	23 h (FDM), 59h (SLA)/N/A	Polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS), nylon powder, photopolymer resin	UltiMaker Extended 2+, DTM Sinterstation 2500CI ATC 3D Systems, Form 2 Formlabs	FDM, SLS, and SLA	NP
		Drill template		N/A				GD
	Yang and Park[13]	Spine model: vertebrae, vertebral disks, paravertebral muscles, ligaments, and nerves	3D Slicer	N/A	Urethane foam, polyurethane rubber, silicone	Creatable D3 A-Team Ventures	N/A	NP
	Xin et al[14]	Lamina positioning guide plate	MIMICS, Rhino	N/A	N/A	N/A	N/A	GD
		Lamina osteotomy guide plate						
		Vertebral osteotomy guide plate						
	Pakzaban[15]	Spine localizer	N/A	N/A	PLA	N/A	N/A	GD
	Lau et al[16]	Lumbar spinal durotomy model	N/A	N/A/$300	PVC polyvinyl chloride plastisol, silicone	N/A	N/A	E/T
	Ozgiray et al[17]	Spine model with C2 (odontoid) fracture and vascularization	3D Slicer	N/A	Polylactic acid	Mass Portal	N/A	NP

Table 1 (*Continued*)

Study		Printed device	Software	Time/cost	Material	Printer	Method	Use
	Dong et al[18]	Artificial vertebra body for treatment of Kümmell's disease	N/A	N/A	Titanium alloy	N/A	EBM	P
	Tredan et al[19]	Implant for cervical disk arthroplasty	MIMICS 22, 3 Matic	N/A	Titanium alloy	EOS M 100 3D Morphic	DMLS	P
	Chatain and Finn[20]	Sacral implant for sacrectomy	K2M's Lamellar 3D Titanium Technology	N/A	Titanium mesh	N/A	N/A	P
	Li et al[21]	Guide template for percutaneous thoracolumbar pedicle screw fixation	MIMICS, MedCAD	N/A	Polylactic acid	FDM-3000, Stratasys	FDM	GD
	Pu et al[22]	Guide template for atlantoaxial pedicle screw placement	MIMICS, Creo	N/A	Ethylene oxide	Formlabs	N/A	GD
	Wang et al[23]	Artificial vertebrae	MIMICS	N/A	Titanium alloy	N/A	EBM	P
	Mobbs et al[24]	Implant with screw trajectories into clivus and C3	N/A	N/A	Titanium	N/A	N/A	GD/P
		Hemivertebra implant			Titanium, bone graft			P
	Tu et al[25]	Drill-guiding templates for pedicle screws	MIMICS, Imageware	2.2–3.7 h/$120–160	Photosensitive resin	N/A	SLA	GD
	Liu et al[26]	Prosthesis for vertebral hemangioma	MIMICS	N/A	N/A	Dongwang Technology	N/A	P
	Zhang et al[27]	Artificial vertebrae	MIMICS	N/A	N/A	N/A	N/A	P
		Pedicle screw path guide plate						GD
		Osteotomy guide plate						GD
Neurovascular	Bairamian et al[32]	Neurovascular model	MeshLab, VMT	N/A/$70	Acrylonitrile butadiene styrene	Flashforge Dreamer	N/A	E/T
	Anderson et al[33]	Aneurysm model	ImageJ	N/A	Polylactic acid and MakerBot flexible filament	MakerBot Replicator 2	FDM	NP
	Faraj et al[8]	Aneurysm model	3D Slicer	N/A	N/A	Da Vinci XYZ	N/A	NP
	Cui et al[34]	Neurovascular model	N/A	N/A	N/A	N/A	N/A	E/T
	Duda et al[35]	Skull model with vascular lesion	3D Slicer, Meshmixer	14–22h/$21.5–26	Polylactic acid	UltiMaker 3	FDM	NP

(*Continued*)

Table 1 (*Continued*)

Study		Printed device	Software	Time/cost	Material	Printer	Method	Use
	Martínez-Galdámez et al[36]	Neurovascular model	N/A	N/A	Silicone	N/A	N/A	E/T
	Xu et al[37]	Aneurysm model	MIMICS	5h/N/A	Photosensitive resin	DWS-XFAB	DLP	NP
	Ravi et al[38]	Basilar aneurysm model	UltiMaker Cura	N/A	UltiMaker PLA	UltiMaker 3	FDM	E/T
	Bae et al[39]	Skull with aneurysm	MEDIP	N/A	Acrylonitrile butadiene styrene and photovoltaic resin	Guider 2 FlashForge and Stratasys J750	FDM and PJ	NP
		Skull with brainstem, thalamus and cavernous malformation						NP
		Skull with lobes, venous sinuses with arteriovenous malformation						NP
	Wang et al[40]	Navigation mold for brainstem hemorrhage	MIMICS	1.5 h/$14	Acrylonitrile butadiene styrene	N/A	N/A	GD
	Lan et al[41]	Aneurysm models: carotid, bilateral, giant aneurysm, small, basilar aneurysms	MIMICS	N/A	Polylactic acid, silicone, and xylene	N/A	N/A	NP
	Jiang et al[42]	Skull model of intracranial arteries with aneurysm	MIMICS	4–5 h/N/A	N/A	Chuangxiang 3D	SLA	E/T
	Wang et al[43]	Skull model of intracranial arteries with aneurysm	N/A	N/A	N/A	N/A	N/A	E/T
	Wang et al[44]	Aneurysm model	MIMICS	N/A/$10–12	Photosensitive resin	Connex Multi-Material MoonRay	N/A	NP
	Wang et al[45]	Skull base with aneurysm model (whole)	MIMICS, ANSYS	13–15h/$300–400	Photosensitive polymers	Connex 350 Stratasys	PJ	E/T
		Aneurysm model (regional)		15–22 h/$55–140	Acrylonitrile butadiene styrene	Jupu 600	FDM	
	Kim[46]	Aneurysm model	BVPF	N/A	Resin	Form 2, Formlabs	SLA	NP
	Zeng et al[47]	Aneurysm model	Vitrea FX	8 h/N/A	N/A	Formlabs	DLP	NP
	Desai et al[48]	NICHE surgical robot for intracerebral hemorrhage	N/A	N/A	CR-CL and CR-BK material (resin)	Form 2	MJP	ND

Table 1 (*Continued*)

Study		Printed device	Software	Time/cost	Material	Printer	Method	Use
Neuro-oncology	Desai et al[48]	MINIR-II surgical robot for brain tumor removal	N/A	N/A	CE-NT and CR-CL material (resin)	MJP 5600 and Objet 350V	MJP	ND
	Faraj et al[8]	Brain model with deep-seated tumor	3D Slicer	N/A	N/A	Da Vinci XYZ	N/A	NP
	Thawani et al[49]	Brain models with glioma	Solidworks	N/A	Polycarbonate polymer	ProJet 6000 3D Systems	SLA	E/T
	Romero-Garcia et al[50]	Brain models with glioma	Custom software	N/A	Plaster powder and cyanoacrylate	Projet 660 Pro	SLA	NP
	Panesar et al[51]	Skull model with craniopharyngioma	TeraRecon	3.75–18.25 h/ $3.41–40.72	Stratasys Vero (resin)	Objet Stratasys J730	PJ	NP
		Skull model with meningioma	MIMICS		Acrylic photosensitive resin	Formlabs	SLA	NP
		Brainstem, trigeminal neuralgia					SLA	NP
	Yang and Wu[52]	Spine tumor model	3 Matic	N/A	Polylactic acid plastic	N/A	N/A	NP
		Needle insertion guide			Photosensitive resin	N/A	N/A	GD
	Ravi et al[38]	Low-grade glioma model	MIMICS	N/A	UltiMaker PLA	UltiMaker 3	FDM	E/T
	Dho et al[53]	Brain model with ventricles, thalamus, caudate nucleus, and tumor	MEDIP	N/A	Acrylonitrile butadiene styrene and photovoltaic resin	Guider 2 FlashForge and Stratasys J750	FDM and PJ	NP
	Damon et al[54]	Brain model with tumor	3D Slicer	1–30 h/$5–10	N/A	Raise3D Pro Plus FDM	FDM	NP
	Yang et al[28]	Vertebrae model with chordoma and vascularization	N/A	N/A	N/A	N/A	N/A	NP
		Artificial vertebral body	MIMICS		Titanium alloy	N/P	N/A	P
	Liao et al[55]	Spine model with osteochondroma	InVesalius, Meshmixer, KiSSlicer	3 h/N/A	Polylactic acid	D-force 300 V2	N/A	NP
	Lan et al[41]	Tumor models: schwannomas, meningioma, brainstem cavernoma, cavernous hemangioma, metastasis, hemangioblastoma, ependymoma, glioma,	MIMICS	8 h/$500	FullCure 705, RGD836, RGD851, FullCure 835, RGD843, and FullCure 930 (rubber-like polymer)	Objet Connex J750 Stratasys	PJ	NP

(*Continued*)

Table 1 (*Continued*)

Study		Printed device	Software	Time/cost	Material	Printer	Method	Use
		lymphoma, and plasmocytoma						
	Graffeo et al[56]	Skull models, brain, and brainstem with schwannoma	MIMICS, 3-Matic	N/A	Ecoflex silicone rubber	Objet 500 Stratasys	PJ	E/T
	Huang et al[57]	Sphenoid bone (sella turcica region), vascularization, chiasm, and macroadenoma models	MIMICS	10–22.5h/N/A	Acrylate resin	N/A	FDM	NP
	Chin et al[29]	Lumbar vertebrae prothesis after tumor surgery	MIMICS	N/A	Titanium alloy	N/A	N/A	P
	Watanabe et al[60]	Skull and brain model with meninges and tumor	Amira, GrabCAD	5–15 h/$350–1,500	Agilus clear and Velo clear (PolyJet materials)	Stratasys J750	PJ	E/T
Neuroendoscopy	Ploch et al[58]	Brain model	FreeSurfer	10 h/$8	Acrylonitrile butadiene styrene	Creator Pro Dual Extrusion FlashForge	N/A	E/T, NP
	Shinomiya et al[59]	Skull and pituitary gland model	Zed View, Freeform	N/A	Acrylic ultraviolet curable resin	Objet500 Connex3	PJ	NP
	Licci et al[61]	Skull with ventricles, tumor, and choroid plexus	MIMICS	4–5 h/$94	PLA and polyvinyl alcohol	Replicator+ MakerBot	N/A	NP
	Duan et al[62]	Skull base with cerebrospinal fluid (CSF) leak origin in middle cranial fossa	MIMICS	6 h/$10	Ivory-colored acrylonitrile butadiene styrene	N/A	FDM	NP
	Huang et al[63]	Skull model for endonasal transsphenoidal surgery	Materialise	12.5–15.3 h/$125–210	Acrylonitrile butadiene styrene	Objet350 Connex	PJ	NP
	Zhou et al[64]	Tumor, ventricular system and brain tissue model	3DSlicer, CrealitySlicer	N/A	N/A	Shenzhen Ender-7	N/A	NP
		Guide plate for endoscopic surgery			Unknown metal			GD
	Ding et al[65]	Skull base with skin for endoscopic endonasal surgery	PolyJet Studio	N/A	N/A	Stratasys J750	N/A	E/T
	Peng et al[66]		3D Slicer	3–6 h/USD20–30	Resin	Ruby 330	STL	GD

Table 1 (*Continued*)

Study		Printed device	Software	Time/cost	Material	Printer	Method	Use
		Guide plate for trigeminal balloon compression surgery						
	Li et al[67]	Extracranial navigation guide plate for intracerebral hemorrhage	N/A	N/A	N/A	CASET 250MC	N/A	GD
Cranioplasty	Panesar et al[75]	Cranioplasty flap implant	3D Slicer, DAVID 3D	24 h/N/A	Somos WaterShed XC 11122	Viper SLA 3D Systems	SLA	P
	Eisenmenger et al[76]	Calvaria model	MIMICS	N/A	VisiJet PXL	ProJet 660 Pro 3D Systems	N/A	NP
		Calvaria model			Acrylonitrile butadiene styrene	UltiMaker 2		
	Cho et al[77]	Preoperative flap planning model	N/A	N/A	N/A	ZPrinter 650 3D Systems	N/A	NP
	Evins et al[78]	Cranioplastic prosthesis	3 Matic	1–3.3 h/> $1	Polymethyl methacrylate	Fortus 250mc Stratasys	FDM	P
	Tan et al[79]	Cranioplasty implants	3D Slicer, MeshMixer, MakerWare	33.3 h/$150	Polylactic acid	MakerBot Replicator 2	FDM	P
	Huang et al[80]	Cranial mesh implants for cranioplasty	ANSYS, SOLIDWORKS	N/A	Preshaped titanium	Renishaw AM250	SLS	P
	Xu et al[81]	Hemicraniectomy implant	Cranial Rebuild	22 h/$40	PLA	Stratasys F370	FDM	P
	Zhong et al[82]	Cranial mesh implant	MIMICS, 3 Matic	N/A	Polyetheretherketone	China are 3D	SLS	P
	Fricia et al[83]	Cranioplasty flap implant	N/A	N/A	Porous hydroxyapatite	N/A	N/A	P
	Kim et al[84]	Cranioplasty flap implant	MIMICS, Magics	6 h/$45	Polymethyl methacrylate	Spectrum Z510	IP	P
	Schön et al[85]	Cranioplasty flap implant mold	MIMICS	5 h/$250 with implant	MED610	Stratasys Objet 30 Prime	PJ	P
	Basu et al[86]	Cranioplasty flap implant mold	3D Slicer	N/A	Project 460	N/A	IP	P
	Kim et al[87]	Cranioplasty flap implant	N/A	N/A	Titanium	N/A	N/A	P
	Kim et al[88]	Cranioplasty flap implant	N/A	N/A	Titanium	N/A	N/A	P
			InVesalius, SolidWorks	20 h/$6,300	Polycarbonate	Stratasys	FDM	P

(*Continued*)

Table 1 (*Continued*)

Study		Printed device	Software	Time/cost	Material	Printer	Method	Use
	da Silva Junior et al[89]	Cranioplasty flap implant mold						
	Baldia et al[90]	Cranioplasty flap implant mold	3D Slicer	N/A	PLA	N/A	FDM	P
	Moiduddin et al[91]	Skull model for cranioplasty	MIMICS, 3 Matic	N/A	ABS	Stratasys Dimension Elite	FDM	NP
		Cranioplasty flap implant		14.5 h/$190	Titanium alloy	ARCAM's EBM	EBM	P
Modulation and stimulation	Chen et al[94]	Burr hole ring for deep brain stimulation (DBS) implants	ProE	N/A	Carbon fiber	N/A	SLA	GD
	Ang et al[95]	Stereotactic frame–specific attachment (jig) for deep brain stimulation surgery	Fusion 360 2.0	N/A	Surgical grade resin	Form 3B+	N/A	GD
	Morris et al[96]	ECoG sulcal electrode sheet	MIMICS, 3 Matic	N/A	SILASTIC MDX4-4210 silicone sheet	Objet PolyJet	PJ	ND
		ECoG gyral electrode sheet						ND
	Dewan et al[97]	Guide plate for depth electrodes in SEEG	N/A	N/A	N/A	N/A	N/A	GD
	Matsushita et al[98]	ECoG electrode casing	MIMICS, 3 Matic	N/A	Resin, silicone sheet	Objet PolyJet	PJ	ND
	Javan et al[99]	Brain model for the simulation of placement of intracranial electrodes	MIMICS, 3 Matic	N/A	Polyamide nylon	EOS EOSINT P730	SLS	NP, E/T

Abbreviations: CJP, ColorJet Printing; DLP, digital light procession; DMLS, direct metsal laser solidification; DMP, direct metal printing; EBM, electron beam melting; ECoG, electrocorticography; E/T, education/training; FDM, fused deposition modeling; GD, guide device; IP, inkjet printing; MJP, MultiJet printing; ND, neurosurgical device; NP, neurosurgical planning; P, prothesis/implant; PJ, PolyJet printing; SEEG, stereoelectroencephalography; SLA, stereolithography; SLM, selective laser melting; SLS, selective laser sintering.

employed a 3D-printed guidance model for osteotomy during complex adult spinal deformity correction, resulting in a 93% screw insertion accuracy—higher than preoperatively designed.

For precise incisions in the spine area, planning by neurosurgery residents and less experienced surgeons can be challenging. To address this and mitigate the risk of malpractice, Pakzaban[15] designed an original surgical instrument for spine localization, facilitating the noninvasive location of the optimal incision site over a targeted spine segment. The study, involving 43 patients, demonstrated 100% device accuracy in locating the incision site overlying the target segment, compared to 81% accuracy from an experienced surgeon. Such devices can be particularly beneficial for less experienced physicians and for training and simulation.

Prosthesis/Implant

3D printing facilitates the creation of custom implants and prosthetics for spinal surgeries, including artificial vertebrae, spinal prostheses, and patient-specific implants. These custom implants, tailored to the patient's anatomy, demonstrate properties akin to those of normal vertebrae in patient-designed models. This enables the treatment of complex cases with relatively short production times, presenting a cost-effective alternative to conventional, more expensive implants.[5,10,18–20,26–29]

In emergency cases, both the design time and the printing time of patient-specific prostheses play a crucial role. Mobbs et al[10] described a case involving a burst fracture of C7 with canal decompression. Using direct metal laser solidification (DMLSA), a patient-specific prosthesis was designed from titanium alloy, exhibiting an excellent fit and primary stabilization. After 15 months of follow-up, the patient lived independently with minimal restriction of motion and no neck pain.

As previously mentioned, printed models can serve as alternatives to traditional implants, resulting in highly precise, patient-specific models that are also cost-effective. Dong et al[18] conducted a study with 28 patients with Kümmell's disease, comparing a 3D-printed artificial vertebra to a titanium mesh cage implant. The 3D-printed vertebrae resulted in less blood loss, faster operation time, and lower incidence of cage subsidence.

Treating sacral chordomas, challenging due to complex anatomy, Chatain and Finn[20] innovatively created a titanium sacral implant for a patient after en bloc sacrectomy using computed tomography (CT) scans and lamellar 3D titanium technology.

Neurosurgical Planning

3D printing allows for the creation of patient-specific anatomical models based on CT or magnetic resonance imaging (MRI) scans, providing surgeons with tangible and accurate representations of the patient's spine. These models facilitate a better understanding of the patient's unique anatomy and pathology, aiding in planning surgical approaches, determining optimal instrument placement, and practicing complex procedures.[6–9,11–13] Models are reconstructed using CT scans and MRI, edited later with Digital Imaging and Communications in Medicine (DICOM) data and 3D printing software such as MIMICS.

In cases requiring high precision in surgical planning, Ozgiray et al[17] created a 3D-printed model for odontoid fracture surgery using CT angiograms (CTAs) and dual-MRI scans. The model provided information about bony and nonbony elements, aiding intraoperative reference for height, thickness, and pedicle and vascular diameters. These details contributed to different variations and the success rate of screw insertion in odontoid fracture treatment.

Education/Training

Surgeons can use 3D-printed spinal models for surgical simulation and training, allowing them to practice complex procedures and refine techniques before actual surgeries. This proves particularly valuable for less experienced surgeons, including neurosurgery residents, dealing with complex cases and unorthodox anatomy.

Lau et al[16] printed a functional, patient-specific lumbar spine phantom for spinal durotomy and dura closure procedures using CT scans. This model included a dural surrogate and tissue-mimicking layers (skin, muscle, and fat). Equipped with a pressurized water system, the model allowed for cerebrospinal fluid (CSF) leakage during durotomy, resulting in a realistic training environment. While the model offers potential for various scenarios, the authors note its high costs.

Neurovascular Applications

Guiding Devices

Similarly to spine applications, guiding devices in neurovascular diseases offer precision, customization, and enhanced surgical planning.[32–48] In instances of intracranial hemorrhage, guiding devices prove crucial for performing procedures such as evacuating blood clots, administering clot-dissolving medications, alleviating pressure on brain tissue, and preventing further damage to critical brain functions.[40,48]

Wang et al[40] manufactured a guiding device for seven patients with brainstem hemorrhage for hematoma puncture drainage, requiring extremely high precision to prevent potential damage to brainstem functions. Utilizing thin-layer CT scans, a guide mold (sheath) was crafted for the operation in just 1.5 hours. Fixed maxillofacial structures, including the orbit, zygomatic arch, external auditory canal, and mastoid process, were modeled for a proper fit to the patient's face. A circular hollow pipe was implemented for the puncture passage.

Desai et al[48] developed a 3D-printed Neurosurgical Intra-Cerebral Hemorrhage Evacuation (NICHE) robot for spontaneous intracerebral hemorrhage, alleviating intracranial pressure to prevent further brain tissue damage. Equipped with electrocautery probes and suction tubing, the NICHE robot softens and evacuates blood clots, featuring sensors and precise tip articulation with a positioning accuracy of 1 mm.

Neurosurgical Planning

Cerebrovascular diseases, including aneurysms and arteriovenous malformations, often present complex and unique anatomical variations.[8,33,35,37–47] 3D printing allows for the creation of patient-specific anatomical models based on medical imaging data. These models aid surgeons in understanding the patient's unique anatomy, facilitating surgical planning. The anatomical accuracy of a properly printed model can be beneficial for surgeons, doubling as an MRI flow phantom.[33] Different materials and colors can be used to represent various structures of the skull and intracranial vascular networks.[35] This detailed information allows for the selection of less invasive techniques after thorough model analysis. Bae et al[39] reported a change in surgical plans for a less invasive method for a patient with an intracranial aneurysm.

Xu et al[37] utilized a 3D-printed aneurysm model for microcatheter adjustment in patients with posterior communicating artery aneurysm. Models were prepared using MIMICS software, and CTA scans were used for scanning. Although the model was printed from photosensitive resin, resulting in greater friction than real blood vessels, the adjusting process was conducted underwater. In eight out of nine cases, microcatheters smoothly reached the target position and remained stable in the packing process. A similar study with resin was conducted by Kim,[46] concluding that the material was too rough to accurately represent the actual vessel.

Education/Training

3D-printed models serve as valuable educational tools for training neurovascular surgeons and residents, simulating surgical scenarios, teaching procedural techniques, and familiarizing trainees with complex neurovascular anatomy in a highly realistic environment for surgical procedures.

Bairamian et al[32] conducted a study comparing three-dimensionally printed models of angiograms versus virtual reality angiograms. Ten neurosurgery trainees performed 15 exercises with the models. Virtual reality angiograms outperformed the 3D-printed models in resolution, zooming ability, ease of manipulation, model durability, and educational potential. However, 3D-printed models exhibited a statistically significant advantage in depth perception and ease of manipulation.

Cui et al[34] assessed the performance of neurovascular interventions in group learning with 3D-printed models versus a control group among neurosurgery residents. Training with printed models allowed for a faster acquisition of knowledge for trainees, with the learning curve entering a steady phase after training with 30 cases, compared to around 40 cases for the traditional training mode to achieve similar effects.

Jiang et al[42] conducted an observational study with 239 students learning neurovascular diseases on three-dimensionally printed models. The experimental group learning from printed models demonstrated higher assessment results, satisfaction, and interest in learning, although there was no significant difference in the improvement of neurovascular knowledge compared to the control group using conventional methods.

Neuro-Oncology Applications

Guiding Devices

Guiding devices in neuro-oncology play a crucial role in the precise surgery of tumors, assisting surgeons in advanced cases with unique anatomy, thereby posing challenges to neurosurgical planning.[8,28,29,48–57]

Desai et al[48] developed Minimally Invasive Neurosurgical Intracranial Robot II (MINIR-II), a three-dimensionally printed patient-specific robot designed for precise removal of skull base tumors under MRI guidance. Equipped with electrocautery probes and suction/irrigation tubes, MINIR-II demonstrated a signal-to-noise ratio (SNR) of less than 2% on a human cadaver head, ensuring its safety during use.

Yang and Wu[52] engineered three-dimensionally printed multifunctional biological scaffolds for spinal tumor surgery, featuring a personalized needle insertion guide made from a photosensitive resin. In an observational study involving 40 patients, postoperative outcomes were analyzed in comparison to a control group. Although the operation time and intraoperative blood loss of the observation group were not significantly different from those of the control group ($p > 0.05$), the postoperative drainage volume and extubating time were significantly lower in the observation group, with a statistically significant difference ($p < 0.05$).

Neurosurgical Planning

Printed models for neurosurgical planning are utilized similarly to the previously mentioned areas of interest. Currently, 3D printers can employ multicolor techniques to represent bone structures, vessels, brain tissue, tumors, and other relevant structures in different and clear ways, enhancing navigation and neurosurgical planning.[51]

Huang et al[57] conducted a retrospective study on 20 patients diagnosed with macroadenoma undergoing endoscopic transsphenoidal surgery. In an observation group of 10 patients, surgical planning was executed on a printed model of the skull with a tumor, employing an adequate technique. The observation group exhibited less operation time, blood loss during the operation, and postoperative complications compared to the control group.

While conventional magnetic resonance images are currently employed for neurosurgical planning in tumor surgeries, Dho et al[53] compared the efficacy of MRI models to three-dimensionally printed models. A study involving 32 neurosurgeons with different experiences revealed that 3D-printed models outperformed standard MRI models in terms of surgical posture changes ($p = 0.0147$) and craniotomy design planning ($p = 0.0072$). Dho et al noted that printed models are especially valuable for neurosurgeons with less experience.

Neuroendoscopy Applications

Guiding Device

Printed guiding devices offer precise positioning and facilitate minimally invasive surgery, reducing the risk of damaging critical brain areas while being easy to implement and cost-friendly.[57–67] Anatomical landmarks, such as Hartel's route for treating trigeminal neuralgia, are valuable for surgical procedures.[68,69] In a study by Peng et al,[66] a comparison between three-dimensionally printed guiding devices and anatomically guided routes for treating trigeminal balloon compression showed better outcomes in the observation group using printed models. The benefits included a significant reduction in foramen ovale puncture time ($p < 0.01$), total operation time ($p < 0.01$), and the number of CT scans ($p < 0.01$), with no significant difference in postoperative complications between the two groups.

Neurosurgical Planning

Printed models contribute to determining the extent of damage from CSF leakage.[70] While high-resolution CT (HRCT) scans provide detailed images of the skull base, their 2D nature can make localizing the origin of the leak challenging.[71,72] Ding et al[65] used a 3D-printed model to accurately identify defect sites and facilitate cranial CSF leak repair. The detailed skull model, created using FDM from CT and MRI scans, revealed visible osseous defects, enabling precise identification of the CSF leak origin and successful surgery. For skull base surgeries, models for endonasal transsphenoidal surgeries can be assembled using CT scans to provide precise guidance and aid in neurosurgical planning.[63–65]

Education/Training

Endoscopic surgeries require thorough training and simulations for neurosurgery residents during fellowship. The nasal cavity's complex anatomy may pose challenges for junior residents, leading to potential malpractice.[73,74] 3D-printed models offer a solution, providing realistic simulations in various scenarios. Ding et al[65] proposed a multicolored printed model with detailed anatomical structures, replaceable facial skin and osseous elements, vascularization, and nerves for endoscopic endonasal surgical training.

Licci et al[61] developed a simulation model for neuroendoscopic ultrasonic ventricular tumor removal from lateral ventricles, incorporating different materials to mimic the varying properties of structures. The use of polyvinyl alcohol, for example, allows for simulating soft-consistency lesions, offering trainees a realistic environment with a highly detailed model.

Ploch et al[58] reported deformable, patient-specific models of the human brain for neurosurgical training, utilizing various techniques (3D printing, molding, and casting) to achieve highly anatomical, tactile, and physiologic properties using cost-efficient gelatin.

Cranioplasty Applications

Cranioplasty serves as a surgical method for fixing cranial defects, requiring a material that fits the defect, achieves complete closure, and prevents the development of infections in autografts or allografts.[75–91] The ideal material should be easily moldable, cost-efficient, infection resistant, and possess appropriate biomechanical properties.[92,93] In a multicenter study by Fricia et al,[83] porous hydroxyapatite patient-specific bone flaps were assessed among 149 patients in France and Italy over 15 years. Complications occurred in 25 patients, with only 9 requiring implant removal due to a late infection. The material demonstrated properties fully comparable to those of other heterologous materials. Kim et al[87] investigated surgical site infections (SSIs) after cranioplasty using various materials among 172 patients who underwent decompressive craniectomy. Only 1 of 48 patients with 3D-printed implants experienced SSI, compared to 13 of 106 with bone implants and 3 of 14 with titanium mesh. Another study by Kim et al[88] compared printed titanium implants to autologous bone and synthetic materials, showing a lower complication rate (3.2 vs. 31.1 and 15.6%, respectively) and a lower postcranioplasty infection rate (3.2 vs. 11.1 and 6.3%, respectively) for printed titanium implants. Three-dimensionally printed molds for custom cranioplasty implant manufacturing are valuable for assessing material properties, such as polymethyl methacrylate (PMMA).[76,79,85,86,89] Baldia et al[90] compared the efficacy of mold-printed PMMA implants to intraoperative hand molding (HM) and bone impression (BI) implants, revealing that mold-printed implants showed the lowest frontal and parietal radiologic asymmetry. Innovative printing techniques like electron beam melting (EBM) are gaining popularity for models, showcasing high anatomical accuracy and shorter production times.[91]

Modulation and Stimulation Applications

Guiding Device and Planning

Accurate placement of microelectrodes with millimeter precision is crucial in deep brain stimulation (DBS) interventions.[94–100] To minimize complications, Chen et al[94] and Ang et al[95] developed a burr hole ring for high-precision placement of microelectrodes in DBS surgeries. In stereoelectroencephalography (SEEG), which is utilized for investigating epileptic foci, Dewan et al[97] printed a skull-anchor platform fixation for SEEG electrode placement. Printing platforms offer ease of use, efficiency, and precision, and are more cost-efficient compared to surgical robots. For nonlesional epilepsy cases requiring invasive intracranial electrodes due to insufficient information from scalp electroencephalogram (EEG), Javan et al[99] created a mesh-like printed brain model. This model aids in visualizing deep brain structures and guides the placement of intracranial EEG (iEEG) and subdural EEG electrodes, providing valuable assistance in neurosurgical planning.

Electrodes and Assisting Devices

Brain surface electrodes, or electrocorticographic (ECoG) electrodes, offer an invasive method for obtaining high-quality neural activity without penetrating the brain tissue. Morris et al[96] introduced patient-specific sheets for sulcal and gyral electrodes. Sulcal electrode sheets allow less invasive insertion, increased electrode density, and adjustable electrode locations, including direction toward the motor and somatosensory banks. Gyral sheets reduce pressure on the brain and enhance the probability of brain tissue contact with electrodes. To minimize environmental noise, a skull casing can be manufactured to shield ECoG electrodes hermetically, providing protection from external impact for more accurate readings.[98]

Discussion

The integration of 3D printing technology into neurosurgery has undoubtedly revolutionized various facets of clinical practice and patient care. This study aimed to delve into the significant advancements, challenges, and potential future directions in the field, considering the diverse applications explored in the reviewed literature.

Applications

One of the primary advancements lies in the precision and customization offered by 3D printing in neurosurgery. Patient-specific anatomical models, implants, and surgical guides have enabled surgeons to approach each case with a tailored strategy.[18–20,64,66,101,102] The ability to create intricate structures with high precision has transformed surgical planning and interventions, particularly in complex procedures such as spine surgeries and neurovascular interventions.[18–20,40,48]

The creation of patient-specific anatomical models based on CT or MRI scans has significantly contributed to enhanced surgical planning.[6–9,20,51,63–65,103] Surgeons can now visualize and interact with accurate 3D representations of the patient's anatomy, leading to a better understanding of unique structures and pathology. This has proven invaluable in preoperative strategizing, instrument placement, and the overall optimization of surgical approaches.

The educational dimension of 3D printing in neurosurgery has witnessed considerable advancements.[16,32,34,42] The development of realistic, patient-specific models for training purposes has facilitated the simulation of complex surgical scenarios. Neurosurgery residents can benefit from hands-on experience in a risk-free environment, refining their skills before engaging in actual surgical procedures.

The application of 3D printing in cranioplasty has demonstrated promising outcomes.[87,91–93] Patient-specific implants, ranging from hydroxyapatite bone flaps to titanium mesh, have shown compatibility, reduced infection rates, and improved overall outcomes.[87,88] The flexibility of 3D printing materials has paved the way for innovative solutions in addressing cranial defects with a focus on biomechanical properties and cost efficiency.

In neuroendoscopy and modulation applications, 3D-printed guiding devices have proven to be essential for precise positioning and minimizing invasive procedures.[66] Additionally, the accurate placement of microelectrodes in DBS interventions showcases the potential for improving outcomes and reducing complications.

Challenges and Considerations

The choice of materials for 3D printing in neurosurgery is a critical consideration. While various materials such as plastics, metals, ceramics, and biological substances can be utilized, their long-term biocompatibility and potential for adverse reactions need careful evaluation. Striking a balance between material properties, cost-effectiveness, and patient safety remains a challenge.

The ethical implications of 3D printing in neurosurgery, particularly concerning patient consent, data security, and the use of 3D printing in research, warrant careful consideration.[104] Additionally, regulatory frameworks need to evolve to keep pace with technological advancements, ensuring the ethical and safe integration of 3D printing into routine clinical practice.

Future Directions

The integration of artificial intelligence (AI) into 3D printing processes holds immense potential.[105–107] AI algorithms can assist in automating the segmentation of medical images, optimizing the design of 3D-printed structures, and predicting patient-specific outcomes.[108,109] This synergy between AI and 3D printing could lead to further precision and efficiency in neurosurgical applications.

Advancements in multimodal imaging fusion could enhance the accuracy of patient-specific models.[110] Combining data from CT, MRI, and functional imaging modalities can provide a more comprehensive understanding of the patient's anatomy, guiding neurosurgeons with enhanced information during surgical planning.

The field of biofabrication, involving the use of living cells and biomaterials for 3D printing, presents an exciting avenue for future exploration.[111] Biomimetic implants and tissues could be created, potentially revolutionizing approaches to neurosurgical interventions, including cranioplasty and neuro-oncology.

Encouraging global collaboration and standardization efforts within the 3D printing community is essential. Establishing common protocols, sharing datasets, and fostering interdisciplinary collaborations can accelerate the pace of advancements and ensure the reproducibility of findings across different health care settings.

Our study has limitations. By employing a nonsystematic approach and omitting specific selection criteria, we aimed to provide a broad overview of current trends. However, future research should focus on in-depth analysis of specific 3D printing applications in neurosurgery. In conclusion, the integration of 3D printing technology into neurosurgery has already demonstrated remarkable advancements with the potential to redefine clinical practices. However, addressing the current challenges and actively pursuing future innovations will be crucial for realizing the full transformative impact of 3D printing in neurosurgery. As technology continues to evolve, neurosurgeons, researchers, and policymakers must collaboratively shape an ethical, safe, and standardized landscape for the ongoing integration of 3D printing into neurosurgical care.

In contemporary neurosurgery, 3D printing plays a pivotal role in preoperative planning, surgical visualization, patient-specific implants, simulation and training, guiding devices, functional neurosurgery, and medical education. As we peer into the future, the applications of this technology are set to expand dramatically. Envision a landscape where 3D printing revolutionizes advanced personalized prosthetics, facilitates the bioprinting of intricate neural tissue, allows for ultrarealistic simulation training devices, and leads to the development of cutting-edge surgical instruments. This ongoing integration of 3D printing, AI, computer-aided imaging, and robotics is poised to reshape the very foundations of neurosurgical practice, promising innovative solutions and unparalleled advancements in terms of costs, operation times, and postoperative complications.

Ethical Statement

Ethical approval was not necessary for the preparation of this article.

Funding

None.

Conflict of Interest

None declared.

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