Review Article

3D printing in neurosurgery: A systematic review

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Abstract

Background: The recent expansion of three-dimensional (3D) printing technology into the field of neurosurgery has prompted a widespread investigation of its utility. In this article, we review the current body of literature describing rapid prototyping techniques with applications to the practice of neurosurgery.

Methods: An extensive and systematic search of the Compendex, Scopus, and PubMed medical databases was conducted using keywords relating to 3D printing and neurosurgery. Results were manually screened for relevance to applications within the field.

Results: Of the search results, 36 articles were identified and included in this review. The articles spanned the various subspecialties of the field including cerebrovascular, neuro-oncologic, spinal, functional, and endoscopic neurosurgery.

Conclusions: We conclude that 3D printing techniques are practical and anatomically accurate methods of producing patient-specific models for surgical planning, simulation and training, tissue-engineered implants, and secondary devices. Expansion of this technology may, therefore, contribute to advancing the neurosurgical field from several standpoints.

Key Words: Additive manufacturing, surgical planning, surgical simulation, three-dimensional printing

INTRODUCTION

Three-dimensional (3D) printing has revolutionized the practice of rapid prototyping since its initial emergence in the 1980s. This technique has enabled the fabrication of physical, 3D models from computer-aided designs through additive manufacturing, in which successive layers of material are deposited onto underlying layers to construct 3D objects.[13] Using this type of manufacturing, traditional intermediary stages of product development including tooling, supply chains, and production lines are eliminated, allowing concepts to be quickly and inexpensively translated into both prototypes and products. Several methods of printing have been developed that leverage unique material properties to selectively cure or fix specific areas on an individual layer. Most notably, fused deposition modeling utilizes a thermoplastic material that hardens after being

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heated during extrusion, whereas stereolithography (SLA) employs a low-power ultraviolet (UV) laser to solidify a liquid photosensitive polymer. Within the last decade, applications for 3D printing technology have expanded greatly in the manufacturing industry as a result of numerous innovations that have markedly reduced production and technology costs, improved the level of accuracy of printed objects, and increased the range of printable materials. These improvements have provided the capabilities to create a variety of products and even make this technology available to consumers for in-home use. Applications within clinical medicine are also emerging due to 3D printing's ability to produce individualized models, devices, and implants that can potentially improve patient care.

The field of neurosurgery, in particular, has experienced substantial progress as a result of the usage of 3D printing. Because most of the surgical procedures and corresponding pathology that neurosurgeons encounter involve intricate, minute anatomical structures that cannot be outwardly observed, neuroimaging has become an integral component of clinical practice.[10] This technology has enabled structures to be noninvasively visualized for both diagnosis and surgical treatment; however, most imaging methods including X-ray, computed tomography (CT), and magnetic resonance imaging (MRI) acquire images in either two-dimensions (2D) or a 3D volume in 2D slices.[37] Therefore, appreciation of the 3D relationships between these structures within a limited surgical aperture is often difficult. 3D printing could provide a practical solution to this issue. With this technology, anatomical structures can be reconstructed from 3D volumes and subsequently fabricated as physical models, which can then be used for surgical planning and education for both patients and trainees. Similarly, the capabilities of 3D printing can be applied to the design of surgical simulations. Simulations provide a realistic representation of the surgical procedure without the risk of potential harm to a patient. 3D printing has enabled the production of customizable, high-resolution simulators that can create a realistic, immersive training environment.[24]

This technology can also serve as a tool for prototyping and production of innovative surgical devices similar to its utility in the manufacturing industry. This application may enable surgeons and researchers to create instruments and implants that correspond to individual patient anatomy for a personalized approach to treatment. Because of recent advancements, biological materials can additionally be utilized as a printing medium to construct engineered, inert scaffolds that can be populated with patient cells for the purpose of transplantation.

Studies involving the incorporation of 3D printing in neurosurgery have focused upon three main areas, i.e.,

the creation of patient-specific anatomical models for surgical planning, training, and education, the design of neurosurgical devices for assessment and treatment of neurosurgical diseases, and the development of biological tissue-engineered implants. In this article, we will review these studies within each subspecialty area within neurosurgery to assess the progress of the field.

MATERIALS AND METHODS

A systematic review of the published literature was performed to assess the current use of 3D printing in the field of neurosurgery. Three medical databases (Compendex, Scopus, PubMed) were searched using keywords for relevant literature between database inception to December 2015. Inclusion criteria included articles referencing both "three dimensional printing" or "additive manufacturing" and "neurosurgery" in addition to common variations of those terms. Results were then manually filtered according to more specific criteria; only human studies related to the brain or spine were considered and no studies concerning craniofacial reconstruction were included. Only studies published in English were included. Table 1 summarizes the application and printing method for each included study.

RESULTS

In total, the described search terms yielded 201 articles from the Compendex database, 288 articles from Scopus, and 265 articles from PubMed. Results were manually reviewed for clinical applications of 3D printing in the field of neurosurgery, and a subset of 36 articles was identified that fulfilled the inclusion criteria. Of the selected articles, 12 were related to cerebrovascular applications, 6 were related to neuro-oncology, 4 were related to functional neurosurgery, 5 were related to spine surgery, 6 were related to catheter and endoscopic applications, 2 were review articles, and 2 were related to other subspecialties of neurosurgery. One article discussed both spinal and endoscopic applications.

Cerebrovascular
Surgical planning and modeling
Cerebral aneurysm surgery requires a thorough understanding of the intricate 3D structure of individual aneurysms in addition to precise knowledge about associated parent vessels and surrounding anatomic structures. Importantly, diagnostic imaging has evolved in past decades from 2D angiography that force surgeons to mentally construct complicated vasculature to 3D computed tomographic angiography (3D-CTA) and digital subtraction angiography (DSA) that provide computationally reconstructed 3D visualizations.[14] However, while surgeons are able to better comprehend the anatomical details with these current techniques, aneurysms

Table 1: Descriptions of three-dimensional printing methods by study[4,25]

	Study	Application	Fabrication Method (s)	Structure (s) Printed	Printer	Material (s)
Cerebrovascular	Anderson *et al*. (2015)[2]	P/M	Fused Deposition Modeling	Aneurysm, parent artery	MakerBot Replicator 2	Polylactic Acid, MakerBot Flexible Filament
	Ionita *et al*. (2014)[7]	P/M	PolyJet Matrix Modeling	Aneurysm, vascular network	Stratasys Objet PolyJet Model 260 V	VeroClear, TangoPlus, SUP705
	Khan *et al*. (2014)[9]	P/M	PolyJet Matrix Modeling	Aneurysm, vascular network	Stratasys Objet 500 Connex	TangoPlus
	Kondo *et al*. (2015)[11]	P/M	Laminating Shaping Method, Binder Jetting	Aneurysm, vascular network, skull	3D Systems ZPrinter 450	Plaster (zp150 powder and zb63 clear binder)
	Mashiko *et al*. (2015a)[14]	P/M & T/S	Fused Deposition Modeling	Aneurysm, parent artery	OPT UP! Plus	Acrylonitrile dutadiene styrene (ABS) plastic, liquid silicone
	Mashiko *et al*. (2015b)[15]	T/S	Fused Deposition Modeling	Aneurysm, parent artery, brain model, skull	OPT UP! Plus	ABS, liquid silicone, urethane
	Namba *et al*. (2015)[19]	P/M	Fused Deposition Modeling	Aneurysm, parent artery	OPT UP! Plus	ABS plastic, molding silicone
	Tai *et al*. (2015)[24]	T/S	Not specified	Skull, brain model, ventricles	Not specified	ABS plastic, high-acyl gellan gum
	Weinstock *et al*. (2015)[33]	P/M	PolyJet Matrix Modeling	Pathologic vasculture, vascular network	Stratasys Objet 500 Connex	Not specified
	Wurm *et al*. (2004)[36]	P/M & T/S	Stereolithography	Aneurysm, vascular network	LaserForm	Stereocol
	Wurm *et al*. (2011)[35]	T/S	Stereolithography/ PolyJet Matrix Modeling	Aneurysm, vascular network, skull	3D Systems SLA-3500, Stratasys Objet 500 Connex	Watershed 11120, multimaterial
	Xu *et al*. (2014)[37]	P/M	PolyJet Matrix Modeling	Vascular network	Stratasys Objet 350 Connex	ABS plastic (VeroClear)
Neuro-Oncology	Ju *et al*. (2012)[8]	ND	Stereolithography	Proton Range Compensator	3D Systems Projet HD	Acrylic plastic
	Menikou *et al*. (2014)[16]	P/M	Fused Deposition Modeling	Head phantom	Stratasys FDM400	ABS plastic
	Oishi *et al*. (2013)[20]	P/M	Selective Laser Sintering	Skull, tumor, brain model, vascular network	Z Corporation zPrinter	Plaster
	Spottiswoode *et al*. (2013)[22]	P/M	Fused Deposition Modeling	Brain model, lesions, fMRI regions	3D Systems Z510 Spectrum	Acylic polymer
	Waran *et al*. (2014a)[31]	T/S	Not specified	Brain model, skin, skull, tumor	Objet	Not specified
	Waran *et al*. (2014b)[30]	T/S	PolyJet Matrix Modeling	Skin, skull, dura, tumor	Stratasys Objet 500 Connex	Multimaterial

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Table 1: Condt...

	Study	Application	Fabrication Method (s)	Structure (s) Printed	Printer	Material (s)
Functional	Hirata et al. (2014)[5]	ND	PolyJet Matrix Modeling	Molds for sheet electrode grids	Objet Geometries PolyJet 3D Printer	Not specified
	Morris et al. (2014)[17]	ND	PolyJet Matrix Modeling	Molds for sheet electrode grids	Objet Geometries PolyJet 3D Printer	Not specified
	Naftulin et al. (2015)[18]	P/M	Fused Deposition Modeling	Skull, brain model	FlashForge Creator Pro, Makerbot Replicator	Polylactic acid (PLA) plastic, ABS plastic
	Troebinger et al. (2014)[27]	ND	Laminating Shaping Method, Binder Jetting	Head cast	3D Systems ZPrinter 350	Not specified
Spine	Bova et al. (2013)[3]	T/S	Not specified	Spinal column	Not specified	Not specified
	Li et al. (2015)[12]	T/S	Fused Deposition Modeling	Vertebrae models	Not specified	Not specified
	Liew et al. (2015)[13]	T/S	Fused Deposition Modeling	Vertebrae models	Stratasys Fortus 250 mc	ABS plastic
	Sugawara et al. (2013)[23]	ND	PolyJet Matrix Modeling	Vertebrae, location guide, drill guide, screw guide	Stratasys Objet 500 Connex	Nonsoluble acrylate
	Whatley et al. (2011)[34]	BI	Fused Deposition Modeling	Intervertebral disk scaffold	Custom 3D Printer	Degradable polyurethane
Endoscopy	Bova et al. (2013)[3]	T/S	Not specified	Skull and skin sections	Not specified	Multimaterial
	Inoue et al. (2013)[6]	T/S	PolyJet Matrix Modeling	Skull	Stratasys Objet 500 Connex	Acrylic plastic
	Ryan et al. (2015)[21]	T/S	Laminating Shaping Method/ Fused Deposition Modeling	Skull, brain model, ventricles	3D Systems zPrinter 650, Stratasys Dimension 1200es	Plaster, ABS plastic
	Waran et al. (2012)[29]	T/S	Powder Deposition Method	Skull, nasal cavity, paranasal sinuses	Not specified	Not specified
	Waran et al. (2013)[28]	T/S	Not specified	Skin, skull, lesions	Not specified	Not specified
	Waran et al. (2015)[32]	T/S	PolyJet Matrix Modeling	Head model, ventricular sytem	Stratasys Objet 500 Connex	Multimaterial
Other	Gatto et al. (2012)[4]	T/S	Fused Deposition Modeling	Neonatal skull phantom	Z Corporation Z510 Spectrum	ZP130 (Powder), ZB58 (Powder)
	Tan et al. (2015)[25]	ND	Fused Deposition Modeling	Skull, cranioplasty implant mold	MakerBot Replicator 2	Polylactic acid (PLA) plastic

P/M: Surgical Planning and Modeling, T/S: Surgical Training and Simulation, ND: Neurosurgical Device, BI: Biological Implant

are paradoxically viewed on a flat 2D computer screen during image review or angiography, making interpretations related to depth difficult. Therefore, physical models, which can be viewed from any angle, represent a potentially more advantageous method of visualization. With the advent of 3D printing, this approach has become a feasible option, enabling physical 3D representations of vascular networks of an individual patient to be produced [Figure 1].[1,26]

Numerous studies have demonstrated that complex vasculature obtained from patient scans can be printed using this technology and have additionally assessed the

accuracy of the resulting models.[2,7,9,11,14,19,33,36,37] One study in particular performed a more comprehensive evaluation across 22 patients with unruptured aneurysms, comparing the reproducibility of the length and thickness

Figure 1: (a) Arteriovenous malformation. Using stereolithography (.STL) files created from DICOM images, the authors have generated models of a patient's vascular malformation. Using specialized software, arterial and venous phases can be segmented within the model. (b, c): Low-grade glioma and white matter tracts. Using diffusion tractography data, a patient's white matter anatomy (corpus callosum, arcute fasciculus, corticospinal tract) and tumor were similarly generated. In the composite model (c), a scaffold has been printed to support the structure during prototyping. Using an alkaline solution, the scaffold is dissolved

of the main arteries and the size of the aneurysm between a 3D-CTA and the printed model.[11] In all studies comprising both qualitative and quantitative assessments, significant differences between preoperative imaging and printed models were only observed in a few minute areas, indicating that these models accurately represent patient anatomy. Table 2 summarizes the findings from these studies. Notably, one report found that most inconsistencies were a result of residual support material within the lumen of the vessels.[7] Visual comparisons to intraoperative observations of patient anatomy also supported the precise replication of anatomical structures with the models,[14,33,36] and more rigorous analysis verified millimeter-level fidelity in 4 patients.[33]

Using these anatomically accurate models, surgical planning can be potentially improved to produce better patient outcomes. In two cases of pediatric arteriovenous malformations, intraoperative time was reduced by 12% compared to matched control cases, suggesting that printed models may facilitate planning.[33] Additional analysis is still necessary to further validate that claim. Namba *et al.* were even able to successfully predetermine the shape of the microcatheter inserted for aneurysm coiling in 10 patients after first performing a validation with the printed model. Printed vascular networks have similarly been utilized to

Table 2: Summary of study findings for the reproducibility of patient anatomy using three-dimensional printed cerebrovascular models

Study	Models (*n*)	Vasculature Printed	Validation Method	Outcome
Anderson *et al.* (2015)[2]	10	Aneurysm, parent artery	Statistical analysis of aneurysm diameter measurements relative to DSA images	No statistically significant group difference ($P=0.4$)
Ionita *et al.* (2014)[7]	2	Aneurysm, vascular network	Computational comparison of re-imaged model and DSA images	Average difference of 120 μm between DSA and model
Khan *et al.* (2014)[9]	1	Aneurysm, vascular network	Visual comparison of model and CTA	Described as accurate representation of aneurysm
Kondo *et al.* (2015)[11]	22	Aneurysm, vascular network, skull	Statistical analysis of measurements of length and thickness of arteries and diameter of aneurysm	No significant difference in length, differences noted in thickness and aneurysm diameter. Favorable reproduction with exception to minute areas
Mashiko *et al.* (2015a)[14]	20	Aneurysm, parent artery	Visual comparison of model to DSA and intraoperative anatomy	Consistent representations with imaging and visual comparison
Namba *et al.* (2015)[19]	10	Aneurysm, parent artery	Visual comparison of model and DSA	No descrepancies observed
Weinstock *et al.* (2015)[33]	4	Pathologic vasculture, vascular network	Comparison of structural measurements from the model and operative anatomy	Less than 10% deviation in measurements
Wurm *et al.* (2004)[36]	13	Aneurysm, vascular network	Visual comparison of model to operative anatomy using intraoperative video	Judged to be a precise repsentation
Xu *et al.* (2014)[37]	2	Vascular network	Quality assessment from clinicians (*n*=8)	7 of 8 clinicians deemed model successful

DSA: Digital Subtraction Angiography, CTA: Computed Tomography Angiography

replicate hemodynamics within an aneurysm[2] and to practice clipping procedures[14] to understand the vascular pathology preoperatively. Individualized 3D printed models have created novel opportunities for surgical planning that could benefit treatment.

Surgical training and simulation
Surgical education has undergone a recent paradigm shift toward simulation-based training as opposed to the traditional experience-based training program. This change reflects the need for a safe teaching environment separated from the risk-inherent operating room, thus enabling teaching faculty to focus on training during simulations and patient care during operations. Other factors have also contributed to the shift including instituted training restrictions that have limited patient interactions, which are essential for procedural learning. The capabilities of 3D printing are well suited for the development of these physical simulators, which is evident from the literature.

One field where learning has generally been constrained to the operating room is aneurysm clipping. With the increase in the treatment of aneurysms through coil embolization and the lack of realistic cadaveric tissue, simulation-based training has become a pertinent training strategy. Mashiko *et al.* created hollow elastic replicas of various aneurysms within their vascular networks from a printed model and provided trainees with the opportunity to gain experience determining the clipping direction, selecting the appropriate clip, and understanding the shape of the aneurysm.[14] Results from a questionnaire following training indicate that trainees found this activity to be helpful in their understanding. Other developed simulators have involved a printed skull along with the cerebral vessels to promote further realism.[15,35] In these models, different materials were also incorporated to more accurately mimic the realistic counterparts such as pliable material for vasculature and aneurysms.

Neuro-oncology
Surgical planning and modeling
Current surgical planning for the resection of brain tumors involves using MRI technology to differentiate between tumor and surrounding brain tissue. Nonetheless, even when this distinction is clear, it can be difficult for surgeons to appreciate the relationships between adjacent anatomical landmarks during the procedure. 3D printing technology has enabled MRI data to be translated into patient-specific models depicting the associations between tumor, skull, vasculature, and surrounding nonpathologic brain tissue [Figure 1].[20,22] Therefore, surgeons can recognize the location and extent of the tumor relative gyral/sulcal patterns and skull features. Models have then been further utilized to

simulate realistic surgical approaches under microscopic observation.[20] Spottiswoode *et al.* additionally included printed regions of functional MRI (fMRI) activation determined from presurgical mapping paradigms in the model to demarcate areas of eloquent cortex that should be avoided in resection.[22]

Printed head models have also had a role in the planning and development of novel treatments for brain tumors. Phantoms that replicate the properties of the skull and cerebral tissue were produced to evaluate the potential for MRI-guided focused ultrasound to be used in the noninvasive thermocoagulation of brain tumors.[16] This method could be a unique alternative to the conventional therapies of surgery, radiotherapy, and chemotherapy.

Surgical training and simulation
Similar to the motives in the field of cerebrovascular surgery, surgical training for the excision of brain tumors has experienced the inclusion of simulation-based training methods. Critically, the use of 3D printers has lead to the development of simulators created from a multitude of materials with varying consistencies and densities.[30] This property has contributed to the reality of the simulation by replicating the handling features of various tissue types. Based on this type of simulator, the performance of trainees with varying levels of experience was evaluated during a brain biopsy procedure in terms of number of attempts and duration of time until successful.[31] Results demonstrated that less experienced trainees required both a greater number of attempts and a longer duration to complete the task, suggesting further practice may affect the learning curve.

Neurosurgical devices
Apart from producing anatomical models for surgical planning or simulation, 3D printing has also been applied to the development of functional, patient-specific devices. One such application for brain tumor treatment has been the creation of a proton range compensator, which provides a conformal dose distribution during proton therapy to protect organs near the targeted tumor tissue.[8] Traditionally, the range compensator is fabricated with a computerized milling machine; however, this machine requires a large facility, noise suppression system, and water purification system. In contrast, Ju *et al.* was able to print a range compensator using 3D printing technology with similar characteristics and reduced system requirements.

Functional
Surgical planning and modeling
Prior to the surgical monitoring and treatment of patients with medication-resistant epilepsy, an interdisciplinary team typically decides where intracranial electrodes will be implanted. However, often times, this planning does not involve defining specific intended locations due to

a difficulty in visualizing possible electrode placements. To address this issue, Naftulin *et al.* have described a streamlined, cost-effective method for printing a patient-specific replica of the brain and skull. As a result, clinicians can place electrodes directly onto the model to plan surgical coverage.[18]

Neurosurgical devices
Intracranial electrode arrays used for treatment and research purposes are generally fabricated with standard electrode spacing and patterning. Therefore, patients receive the same electrode grids regardless of their gyral and sulcal patterns and intended recording area. 3D printing technology has enabled researchers to create printed molds from which personalized silicone sheets with embedded electrodes can be produced.[5,17] For instance, in one case, an electrode array was designed with electrodes more densely covering primary motor cortex for motor-based brain computer interface recordings. This method provides flexibility in terms of the location and distribution of electrodes within the grid.

Rapid prototyping with additive manufacturing has also proven to be a valuable tool in noninvasive forms of recording brain activity, as in magnetoencephalography (MEG). To maximize the signal to noise (SNR) ratio and minimize the error introduced as a result of varying head positions within the MEG scanner, a printed patient-specific head cast was developed to conform to both the patient's head and the inside of the helmet.[27] This device acts to reduce patient movement during a session and, more critically, between sessions, which can lead to improved co-registration between the sensors and the source of the brain activity. Troebinger *et al.* estimated that this method reduced error to the order of a millimeter and increased SNR between sessions by a factor of 5 compared to conventional strategies.

Spine
Surgical training and simulation
Identification and understanding of anatomy is a fundamental component to learning about the surgical treatment of spine fractures. Neuroimaging techniques, such as CT and MRI, have substantially advanced the capabilities to recognize these fractures, however, they can still be challenging to interpret when visualized as 2D image slices. Li *et al.* investigated whether printed 3D representations of such images could promote a greater understanding of pathology by medical students compared to 2D CT images and 3D virtual renderings.[12] This large-scale study revealed that students were significantly better able to identify complex fracture anatomy with the printed models as compared to the 2D CT images. While no significant difference in accuracy existed between the students using the printed model and virtual rendering, students with the printed model

completed the study in a shorter duration. An additional study qualitatively assessed the effect of 3D printed models on understanding for surgical trainees.[13] Nearly all trainees responded that the physical models enhanced their spatial knowledge of patient anatomy more than viewing the 2D CT images alone.

Procedural skills for spinal surgery have similarly been addressed with 3D printing technology in the form of simulation. Analogous to their ventriculostomy simulator, Bova *et al.* have developed a tool that utilizes a 3D spinal construct paired via surgical instruments to a virtual interface that displays corresponding patient images.[3] This technique enables trainees to determine the correct surgical trajectory based on image-guided software, mimicking a realistic surgical environment.

Neurosurgical devices
Pedicle screw fixation is a common spinal procedure that has a potential risk of injury associated with the accuracy of implantation. Drill templates have been previously developed to combat this issue; however, significant deviations have still been recorded. Therefore, Sugawara *et al.* have designed a multistep, patient-specific screw guide that locks onto the lamina to prevent erroneous movement.[23] These templates were printed for individual vertebrae and evaluated using 58 pedicle thoracic screws on 10 patients. Initial findings confirm no incidences of injury and an average deviation of less than 1 mm.

Biological implants
The field of spinal surgery has additionally begun to explore tissue-engineered solutions using 3D printing for the treatment of intervertebral disk (IVD) degeneration. Efforts have currently focused on a method to regenerate the IVD as an alternative to spinal fusion and artificial disk replacement. This regeneration has been attempted with elastic scaffolds created from depositing successive substrate layers and seeding the scaffold with cells.[34] Preliminary testing has demonstrated that scaffolds have comparable properties to native tissue. Further investigation is still required to produce a clinically available implant.

Catheter and endoscopic applications
Surgical training and simulation
Another common and related neurosurgical procedure that has been the subject of interest for simulation development using rapid prototyping is ventriculostomy.[3,21,28,32] These simulators all consist of a reusable base segment that represents either the face or lower portion of the skull and a disposable segment where users execute the procedure. An important advancement in some of these devices has been the addition of a fluid-filled ventricular system that can provide variable ventricular pressures to simulate pathology.[21,32] In contrast, another simulator described in Bova *et al.*

leveraged an electromagnetic tracking system registered to a virtual depiction of the positioning once the layers of skin, skull, and dura mater are traversed.[3] Previously designed simulators were state-of-the-art virtual haptic-based systems; however, these systems have high-associated costs that are not feasible for many institutions. The introduction of 3D printing has, thus, triggered the development of more affordable simulators that still retain realistic representations.

Transnasal sphenoid endoscopy for pituitary tumor removal has been another important area that has pioneered the integration of 3D printing in simulation development. In associated studies, skull replicas have been created to practice and assess surgical approaches guided by endoscopy.[6,29] An advantage to using a printed skull for these simulations is its ability to be registered to the surgical navigation system.[28,29] This capability more accurately reflects the surgical procedure and allows the model to be paired in real-time with the corresponding neuroimages.

DISCUSSION

Rapid prototyping 3D-printing technologies provide a practical and anatomically accurate means to produce patient-specific and disease-specific models. These models allow for surgical planning, training and simulation, tissue-engineered transplants, and devices for the assessment and treatment of neurosurgical disease. Expansion of this technology in neurosurgery will serve practitioners, trainees, and patients.

Recent publications have described a range of applications for 3D printing in the various subspecialties of neurosurgery. These fields include cerebrovascular, neuro-oncologic, spinal, functional, and endoscopic neurosurgery, and relate to the treatment of pathologic cerebral vasculature, brain tumors, spinal cord conditions, treatment-resistant neurologic disorders, and remotely located pathology, respectively. Each field has uniquely applied 3D printing to advance surgical planning, training, and treatment.

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Conflicts of interest
There are no conflicts of interest.

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