



# 3D-Printed Disease Models for Neurosurgical Planning, Simulation, and Training

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Spatial insight into intracranial pathology and structure is important for neurosurgeons to perform safe and successful surgeries. Three-dimensional (3D) printing technology in the medical field has made it possible to produce intuitive models that can help with spatial perception. Recent advances in 3D-printed disease models have removed barriers to entering the clinical field and medical market, such as precision and texture reality, speed of production, and cost. The 3D-printed disease model is now ready to be actively applied to daily clinical practice in neurosurgical planning, simulation, and training. In this review, the development of 3D-printed neurosurgical disease models and their application are summarized and discussed.

**Key Words :** 3-dimensional printing · Stereolithography · Surgical navigation · Simulation training.

## INTRODUCTION

Spatial perception of brain structures is a key attribute of competent neurosurgeons. Predicting the location of the lesion in three-dimensional (3D) space before surgery is more important for neurosurgeons than other surgeons because brain lesions have to be approached through a difficult process called craniotomy, and it is almost impossible to search for lesions during surgery by recklessly scouring brain tissue. In addition, all anatomical information of neurosurgical patients is obtained from sophisticated neuroimaging modalities, such as computed tomography (CT) or magnetic resonance imaging, which are usually presented in two-dimensional images of each axis. To succeed in brain surgery in a safe and efficient way, neurosurgeons must spatially reconstruct and simulate brain

structures and lesions in their head based on neuroimages. This ability of spatial perception of brain structures can be acquired through repeated training of image interpretation and virtual reconstruction, followed by real-world verification at the surgical site of the patient. However, it is difficult for trainees to be given sufficient opportunities to practice in such a harsh recent training environment. Traditionally, surgical training using cadaver dissection has been preferred to compensate for the lack of clinical experience, but even this is becoming increasingly difficult due to problems with the supply and demand of cadavers as well as ethical and biosafety issues.

Recent advancements in 3D printing technology in medicine provide an opportunity to alleviate these difficulties. The medical 3D printing field can be divided into four main fields<sup>60</sup> : 1) anatomical models for surgical planning, simula-

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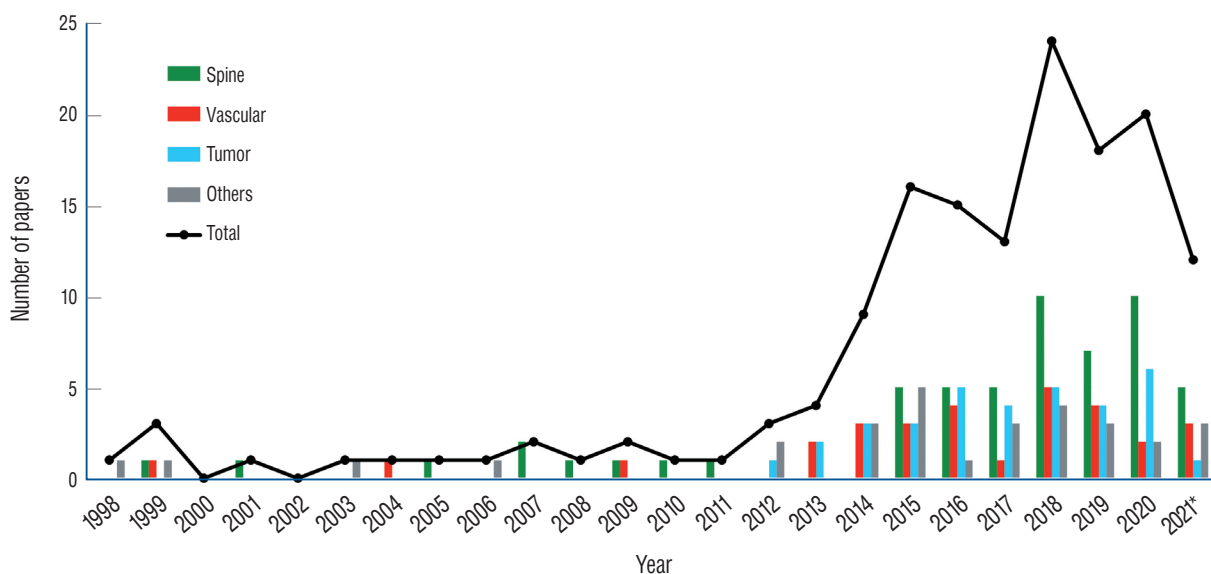
tion, and training; 2) medical devices including bioimplants, orthoses/prostheses, and surgical instruments including guide templates; 3) tissue engineering devices or bioprinting organs/tissue models; and 4) drug formulations. However, the scope of application of 3D printing technology in the medical field is growing rapidly to novel applications. In this review, the focus will be on the current development and application of 3D-printed disease models for surgical planning, simulation, and training in the neurosurgical field.

### DEVELOPMENT OF 3D-PRINTED DISEASE MODELS FOR NEUROSURGICAL DISEASES

The origin of the current 3D printing technology concept dates back to the early 1980s, allowing the manufacturing of objects by depositing materials layer by layer using a stereolithography apparatus (SLA)<sup>44</sup>. The first reported human anatomical model using an SLA was a skull model constructed from CT images in 1990<sup>67</sup>. However, it was in the early 2000s that 3D printing technology began to be applied to various medical fields<sup>47</sup>. Thanks to technical advances in 3D printing methods, diversification of source materials, and easy availability of hardware, an appropriate cost-effectiveness of 3D printing have been achieved, and public interest exploded in the 2010s.

In the field of neurosurgery, early efforts to create 3D-printed disease models for surgical planning or educational purposes were attempted in spinal disease<sup>19</sup> and cerebral aneurysm<sup>20</sup>. Approximately 150 papers covering neurosurgical disease models built for surgical planning, simulation and training have been published in the English literature to date (Fig. 1). Most of the models were developed for the purpose of presurgical simulation of complex and difficult cases, or education/training of surgical techniques and anatomy. The three major limitations of the early 3D-printed disease models were precision and texture reality, speed of production, and cost acceptability<sup>81</sup>. However, with the continued development of technology, these limitations have been resolved, and barriers to entering the clinical field and medical market have almost been completely removed.

From a developer's point of view, the 3D-printed neurosurgical disease model can be divided into two categories. One is a patient-specific model, and the other is a standardized model (Table 1). The patient-specific model is customized one for the specific case, which is usually a complex, rare and challenging disease form to be treated surgically. The purpose of the patient-specific model is to improve the clinical outcomes by enabling preoperative surgical planning and simulation as well as by aiding communication. The production of patient-specific models must be completed in a short time with a single order, and its production pipeline must be maintained to



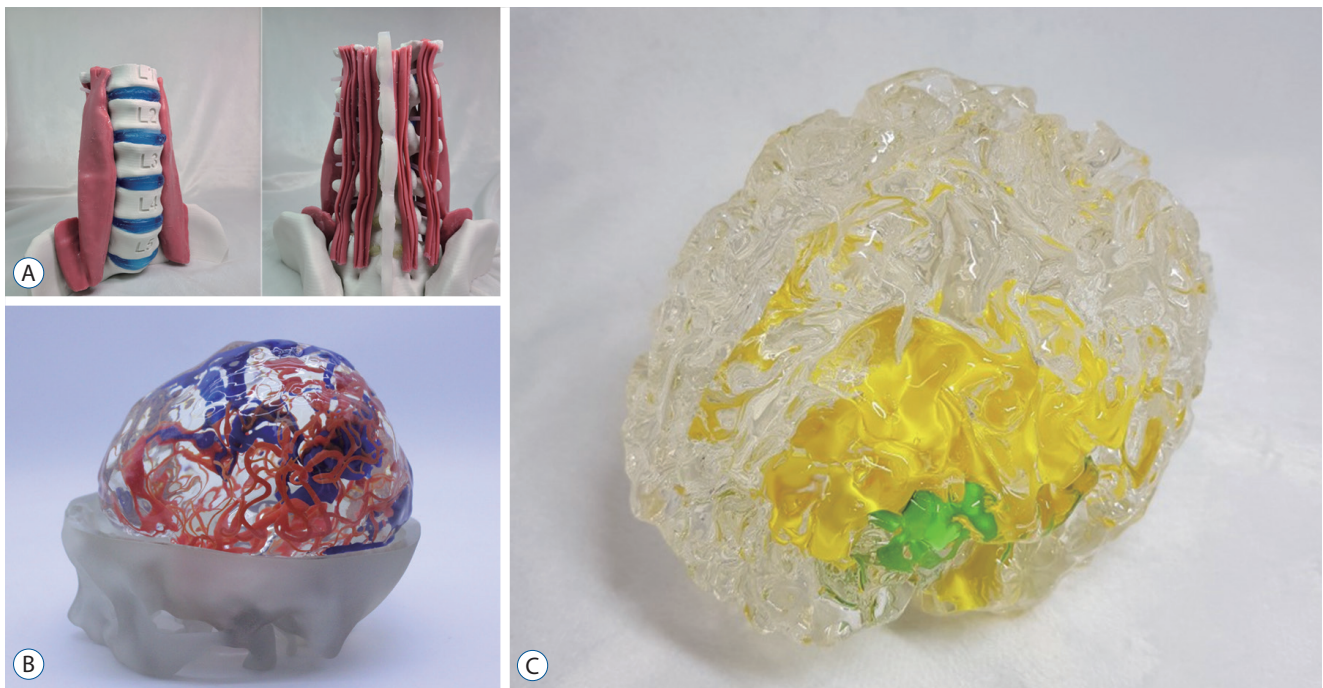
**Fig. 1.** Annual distribution of the number of papers on three-dimensional (3D)-printed disease models for surgical planning, simulation, and training in the neurosurgical field published in English literature. \*From January to August.

continuously handle multiple orders. High-risk surgical diseases, such as deep-seated brain tumors and complex cerebrovascular or spinal diseases, are expected to be frequent indications for patient-specific models. The representative patient-specific 3D-printed disease models are shown in Fig. 2. On the other hand, the standardized model is developed according to

an event or educational program, and then copies are produced and supplied. Therefore, it is not necessary to continuously maintain the production pipeline of the model if mass production is performed at once. Moreover, the standardized model can lower the price compared to the patient-specific model due to cost reduction by mass production. Since the

**Table 1.** Classification and characteristics according to the purpose of use of the 3D-printed neurosurgical disease models

	Patient-specific model	Standardized model
Customer	Surgeon, patient	Trainee, student
Production type	Singular, customized	Plural, replica
Purpose	Improvement of clinical outcome	Acquirement of knowledge and experience
Usage	Surgical planning, simulation, and communication	Training and education
Production speed	Critical	Not critical
Production pipeline utilization	Continuously on demand	Periodically on event
Cost	Relatively expensive	Discount factors exist
Disease form	Challenging, rare disease	General, representative disease
Major indications	Deep seated brain tumor Complex cerebrovascular disease Complex spinal disease	Skull base surgery Endoscopic surgery Cerebrovascular disease Endovascular surgery Spinal instrumentation Functional neurosurgery



**Fig. 2.** The representative patient-specific three-dimensional (3D)-printed disease models. A : Spinal disease model of lumbar stenosis. B : Cerebrovascular disease model of arteriovenous malformation. C : Brain tumor model of insular glioma.

purpose is training and education, the target disease condition for standardized models is usually a representative and general. The standardized model is expected to be utilized in the fields of skull base surgery, endoscopic surgery, endovascular surgery, spinal instrumentation, and functional neurosurgery, where a hands-on workshop or cadaver dissection course is actively held.

## SPINAL DISEASE MODELS

Spinal disease is the most active field in neurosurgery in which 3D printing technology is vigorously applied<sup>28</sup>. In 1999, the first 3D-printed spinal disease model using an SLA was introduced for the surgical planning and simulation of complex spinal disease<sup>19</sup>. Since then, more than 50 papers have repeatedly confirmed the benefit of 3D-printed spinal disease models in the planning and execution of surgery by providing insights into optimum screw trajectories, appropriate instrument or implant selection, detailed information on anatomical structures, geometrical measurement of deformity degrees, and establishment of surgical goals. Moreover, several studies have demonstrated a reduction in operation time and perioperative blood loss by using 3D-printed spinal disease models<sup>29,59,111,114</sup>. The material used to manufacture spinal disease models continued to be developed through various attempts starting from plastic, so that the texture can be similar to the actual spine bone<sup>19,39,89,96</sup>. The model extends its scope to physiological or flexible models<sup>14,108</sup>. The majority of 3D-printed spinal disease models have been patient-specific models applied in real clinical practice to improve clinical outcomes. Similar to other 3D-printed disease models, 3D-printed spinal disease models have been shown to improve patient communication and education<sup>48,119,120</sup>. Patient-specific templates for the guidance of instrumentation are another active field of the application of 3D printing technology in spine surgery. However, a standardized model of spinal disease has been actively developed relatively recently and is well utilized in training and education<sup>5-7,9,15,16,38,79,110</sup>.

## CEREBROVASCULAR DISEASE MODELS

The earliest and most common target disease for the 3D-

printed cerebrovascular disease model is intracranial aneurysm<sup>1,4,20,25,27,49,50,57,90,97,112</sup>. The texture and elasticity of the developed aneurysm model were realistic enough to simulate surgery<sup>2,55,58,69,84</sup>. The 3D-printed aneurysm model was developed not only for conventional surgical planning but also for endovascular treatment<sup>53,74</sup>. Another major target disease for 3D-printed cerebrovascular disease models is arteriovenous malformations, which may benefit from reduced operation time by helping presurgical planning<sup>20,86,93,106,115</sup>. Other cerebrovascular models, such as dural venous sinus or cavernous angioma models, were also attempted<sup>134,95</sup>. For efficient presurgical planning, all models that include adjacent structures as well as vascular lesions have been shown to be more useful for surgical planning than regional models constructed with only vascular structures<sup>2,98</sup>. The 3D-printed cerebrovascular disease model is also actively used for simulation experiments. One good example is cerebrovascular stenosis or occlusion models, which have successfully demonstrated meaningful results in a variety of experimental settings<sup>11-13,23,65,70,113</sup>. The standardized model of cerebrovascular disease for educational purposes has been attempted from the relatively early stage of development<sup>24,46,56,73,99,103</sup>. From an educational standpoint, it has been reported that virtual reality models are superior to 3D-printed models in terms of resolution, zoom capability, and model durability, but 3D-printed models have significant advantages in depth perception and ease of manipulation compared to virtual reality models<sup>3</sup>.

## BRAIN TUMOR AND SKULL BASE LESION MODELS

The 3D-printed brain tumor model is a latecomer compared to spinal or cerebrovascular disease models. This is because brain tumors are less stereotypical and individual variances in tumor location, size, and texture are so great that only case-by-case experiences are meaningful. Therefore, the fabrication process for individualized complex patient-specific models has been less cost-effective to readily enter clinical practice. However, it is obvious that presurgical planning using 3D-printed brain tumor models can help ensure safe and successful surgeries especially for less experienced neurosurgeons<sup>76,78</sup>. The cost-effectiveness limit of the customized model is gradually being solved with the development of tech-

nology<sup>21,88</sup>). The patient-specific 3D-printed brain tumor model production platform that can cope with the speed of urgent clinical practice has been developed and is now ready to use<sup>22</sup>). The use of multiple and transparent materials for the realization of complex structures and the brain has enabled much more realistic and useful results for 3D-printed brain tumor models<sup>22,36,51,102,117</sup>). A functional navigator approach that applies tractography results to a 3D-printed brain tumor model has also been attempted<sup>30,33,94</sup>.

On the other hand, skull base surgery is the most favorable field for both patient-specific and standardized 3D-printed disease models<sup>37,62,82</sup>). As many skull base surgery workshops are being held worldwide, skull base surgery is a field where standardized models are actively produced and applied for education and training<sup>63,103</sup>). The development of a model capable of drilling bones such as real bone plays a significant role in invigoration<sup>52,54,77</sup>). The 3D-printed skull base tumor model has been actively used for endoscopic skull base surgery training as well, where the keyhole anatomy is a steep barrier of the learning curve<sup>42,64,71,75,87,92,101,109,118</sup>). Moreover, evidence has shown that its application to endoscopic brain tumor surgery enhances surgical outcomes by aiding in reconstruction or by reducing the operation time, blood loss, and complication rate<sup>26,43</sup>).

## OTHER BRAIN DISEASE MODELS

Surgical planning for reconstructive cranioplasty after craniofacial resection, skull anomaly correction, and tumor resection can be greatly supported by 3D-printed models<sup>18,31,40,72</sup>). Endoscopic surgery for ventricular lesions, including ventriculostomy, is another popular subject of training programs using 3D-printed models<sup>8,32,41,61,85,91,104,107</sup>). The patient-specific 3D-printed myelomeningocele model was fabricated to plan the correction of spinal deformity<sup>45</sup>). Models of other types of congenital anomalies, such as meningoencephalocele model, were also created for surgical planning<sup>17</sup>). The 3D-printed model could be helpful for repairing cerebrospinal fluid leakage sites by designing an appropriate flap to cover<sup>35</sup>). The quality assurance of radiosurgery could be tested by a 3D-printed patient-specific phantom<sup>66</sup>). More realistic models with special effects have been developed for training various neurosurgical skills<sup>10,68,80,107,116</sup>).

## FUTURE PERSPECTIVES

Despite the rapid development and popularization of 3D printing technology, there is still no consensus on its usefulness for neurosurgical planning, simulation, and training in the clinical field. The clinical entry of 3D printing technology is strictly regulated by medical administrative authorities of each country and only partially allowed officially for minor subjects. This is because there is a lack of large-scale studies that can prove its clinical effectiveness expressed by general clinical variables, which is practically difficult to implement because it targets complex and uncommon cases. However, the real value of the 3D-printed disease model is to lower the entry barrier for high-level surgery by allowing neurosurgeons with less experience to perform difficult surgeries more safely and successfully. This is more important in the current training environment with limited opportunities. Continuing efforts to shorten the learning curve for high-level neurosurgeries using a 3D-printed model will also help resolve the trend of medical care concentration in high-volume hospitals.

The increasing affordability and convenience of hardware have fueled advances in biotechnological 3D printing. Their application in daily clinical practice in neurosurgery for the purpose of presurgical planning, simulation and training is now feasible<sup>22,83</sup>). The accuracy of the full-scale model is comparable to that of a navigation system<sup>100,105</sup>). The 3D-printed disease model is expected to play a mediating role between the current conventional navigation system and the future augmented reality-based navigation system. The clinical experience accumulated with the 3D-printed disease model will be a valuable basis for the development of futuristic navigation systems.

## AUTHORS' DECLARATION

### Conflicts of interest

Chul-Kee Park has been editorial board of JKNS since September 2020. He was not involved in the review process of this original article. No potential conflict of interest relevant to this article was reported.

### Informed consent

This type of study does not require informed consent.

## Author contributions

Conceptualization : CKP; Writing - original draft : CKP; Writing - review & editing : CKP

## Data sharing

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