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Clinical Applications of Additive Manufacturing Models in Neurosurgery: a Systematic Review

Aplicações clínicas de modelos de manufatura aditiva na neurocirurgia: uma revisão sistemática

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Abstract

Introduction Three-dimensional (3D) printing technologies provide a practical and anatomical way to reproduce precise tailored-made models of the patients and of the diseases. Those models can allow surgical planning, besides training and surgical simulation in the treatment of neurosurgical diseases.
Objective The aim of the present article is to review the scenario of the development of different types of available 3D printing technologies, the processes involved in the creation of biomodels, and the application of those advances in the neurosurgical field.
Methods We searched for papers that addressed the clinical application of 3D printing in neurosurgery on the PubMed, Ebsco, Web of Science, Scopus, and Science Direct databases. All papers related to the use of any additive manufacturing technique were included in the present study.
Results Studies involving 3D printing in neurosurgery are concentrated on three main areas: (1) creation of anatomical tailored-made models for planning and training; (2) development of devices and materials for the treatment of neurosurgical diseases, and (3) biological implants for tissues engineering. Biomodels are extremely useful in several branches of neurosurgery, and their use in spinal, cerebrovascular, endovascular, neuro-oncological, neuropediatric, and functional surgeries can be highlighted.

Keywords
► 3D printing
► biomodel
► neurosurgery

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Conclusions Three-dimensional printing technologies are an exclusive way for direct replication of specific pathologies of the patient. It can identify the anatomical variation and provide a way for rapid construction of training models, allowing the medical resident and the experienced neurosurgeon to practice the surgical steps before the operation.

Resumo

Introdução as tecnologias de impressão 3D proporcionam uma forma prática e anatômica de reproduzir modelos precisos e feitos sob medida dos pacientes e das doenças. Estes modelos podem permitir o planejamento cirúrgico, além de treinamento e simulação cirúrgica no tratamento de doenças neurocirúrgicas.

Objetivo o objetivo do presente artigo é revisar o cenário de desenvolvimento de diferentes tipos de tecnologias de impressão 3D disponíveis, os processos envolvidos na criação de biomodelos e a aplicação destes avanços no campo neurocirúrgico.

Métodos Procuramos por estudos que abordaram a aplicação clínica da impressão 3D em neurocirurgia nas bases de dados PubMed, Ebsco, Web of Science, Scopus e Science Direct. Todos os artigos relacionados ao uso de qualquer técnica de fabricação aditiva foram incluídos no presente estudo.

Resultados Estudos envolvendo impressão 3D em neurocirurgia estão concentrados em três áreas principais: (1) criação de modelos anatômicos adaptados para planejamento e treinamento; (2) desenvolvimento de dispositivos e materiais para o tratamento de doenças neurocirúrgicas, e (3) implantes biológicos para a engenharia de tecidos. Em vários ramos da neurocirurgia, os biomodelos são extremamente úteis. Pode-se destacar o uso em cirurgias de coluna, cerebrovasculares, endovasculares, neuro-oncológicas, neuropediátricas e funcionais.

Conclusões As tecnologias de impressão 3D são uma forma exclusiva de replicação direta das patologias específicas do paciente. Elas podem identificar a variação anatômica e fornecer uma maneira para a construção rápida de modelos do treinamento, permitindo que o residente médico e o neurocirurgião experiente pratiquem as etapas cirúrgicas antes da operação.

Palavras-chave
- impressão tridimensional
- biomodelos
- neurocirurgia

Introduction

The continuous advances in computer sciences brought several perspectives to the field of medicine. The possibility of visualization of internal organs using ultrasound (US) and computed tomography (CT) was followed by a significant progress with a better definition of the images through magnetic resonance imaging (MRI), and the medical horizons became wider. More recently, the virtual database could be changed in format, and the two-dimensional (2D) data became three-dimensional (3D) images. Ever since, with the improvement of the hardware and software myriad, the 3D virtual medical image became more convenient, easier to use, and with better resolution and interaction with the user.[1,2]

The technological advances have been driven by the needs of the industry and have been put forward by the advent of additive manufacturing (AM) techniques. This, in the field of the medicine, allows the production of 3D models of human structures, named as biomodels, beginning with data acquired from imaging exams.[1,3]

Currently, AM has been used by physicians to improve the precision of the diagnosis and of surgical planning and as a teaching tool for medical students and residents. It is particularly useful the surgeons, since 2D images cannot be easily understood in relation to the anatomical structures and complex anatomical irregularities.[4]

The available imaging exams can ensure a good visualization of the morphology of the organs to the surgeons; however, on some occasions, they are not effective for an appropriate surgical planning. Although digital graphs have become very similar to reality, the simulation of a surgical procedure remains difficult and is far from being applied, even when advanced technologies are adopted. Virtual reality simulators were developed for neurological surgery in an attempt to solve this problem. However, they are based on an extensive use of graphs with limited tactile feedback. Despite supplying 3D virtual images, the interpretation of these images depends on the rationale of the surgeon, who needs to transform the 2D images into 3D virtual images. On the other hand, real models of cerebral structures can provide a fertile tactile expression with no need of any visuospatial capacity of the surgeon to process the 2D images, since a touchable and real 3D model is available.[5]

In the surgical field, AM application reaches specialties such as bucomaxillofacial surgery, otolaryngology (ORL), orthopedics, cardiac surgery, and neurosurgery.

Bucomaxillofacial surgery applies 3D models for surgery planning in orthognathic patients, since the anatomy and the procedures in this area are quite complex. Three-dimensional printing technologies provide better functional and esthetic results, and increased satisfaction of patients due to a precise surgical planning.[6–9]

In the ORL field, the procedures can represent significant challenges, even for the most experienced surgeons, during resection of infiltrative tumor diseases and for the reconstruction of anatomical structures, mainly in the endoscopic approach and for skull base diseases. The use of AM allows the production of specific models from the patient, providing better surgical planning and preoperative simulation.[10]

In orthopedics, this technology affected mainly the surgical planning, being applied to spine, hip, pelvis, and shoulder lesions. Tailor-made prostheses are able to be adapted to the anatomy of each individual.[11]

Cardiovascular diseases also obtain benefits, since the biomodels can play an important role in the diagnosis and treatment. The technology is particularly useful to surgical and endovascular interventions, such as arterial endoprosthesis implantation. Likewise, in the literature, many reports described the use of biomodels in the treatment of valvar diseases.[12–14]

In neurosurgery, AM has numerous applications, which will be presented in detail.

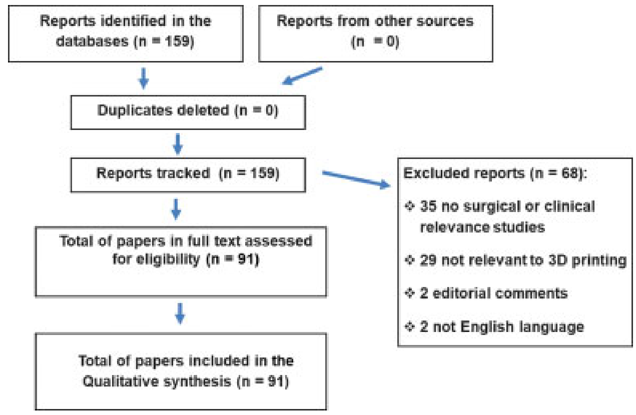
Methods

We searched for papers that addressed the clinical application of 3D printing in neurosurgery. All articles related to the use of any AM technique were included in the present study. The exclusion criteria were: studies with no surgical or clinical relevance, not relevant to 3D printing, editorial comments, and image submissions. Articles were searched using the PubMed, Ebsco, Web of Science, Scopus, and Science Direct databases on December 30, 2018. Both Mesh terms and key terms were used to capture any publications not yet indexed. As keywords for the search, the following terms were used: *Printing, Three-Dimensional* [Mesh], *3D Printing, Three-Dimensional Printing*, and *Neurosurgery*. There were no limits for the time of publication. A total of 159 articles were retrieved, from which 68 were excluded. Finally, 91 articles were selected for review (►**Fluxogram 1**).

Results and Discussion

Additive Manufacturing: Concept

Since its beginning, in the 1980s, AM was revolutionary in the development of objects. The term AM, formerly called rapid prototyping, is popularly known as 3D printing. It designates a gathering of technologies for manufacturing physical objects directly from a database that was generated by computer-aided design (CAD). These methods are quite peculiar, since the materials can be joined or bound, layer by layer, aiming to constitute the projected object.[3]



Fluxogram 1

The term "rapid" associated to those processes is relative, since the construction of some prototypes can take from 2 to 72 hours, depending on the size and complexity of the object.[15–17]

A specific software that consists of the interface between the 3D model (CAD) and the AM machine decomposes the CAD model into several thin layers, which are piled one by one. The process of AM combines layers of material with the purpose of creating a solid object. The creation of objects with complicated internal characteristics is performed by the additive nature of this process, which cannot be achieved through other processes such as, for instance, machining, milling, and drilling, which are subtractive processes.[18,19]

Three-dimensional printing consists of a process to build 3D objects starting from a digital file. In this process, a 3D digital object is created using the design software (CAD). These virtual 3D objects are saved in a file whose format is recognized by the 3D printer (usually, in the STL format).[20]

All existing AM processes, until now, consist of five basic stages (►**Figs. 1**, **2** and **3**):

1. Creation of a CAD model of the object that is being projected;
2. Conversion of the CAD file into an STL file;
3. Decomposition of the STL file into thin transversal layers;
4. Physical construction of the model, piling up one layer on another;
5. Cleaning and finishing of the model.

In this technology, several different processes of production are involved. Depending on the 3D printing process, the production of the model can be classified into 7 categories, according to the ISO/ASTM 52900 standard (2015)[19,21–23]:

1. Binder jetting: when a liquid bonding agent is selectively deposited to join powder materials;
2. Directed energy deposition: a process in which focused thermal energy is used to fuse materials by melting as they are being deposited;
3. Material extrusion: when a material is selectively dispensed through a nozzle or orifice;

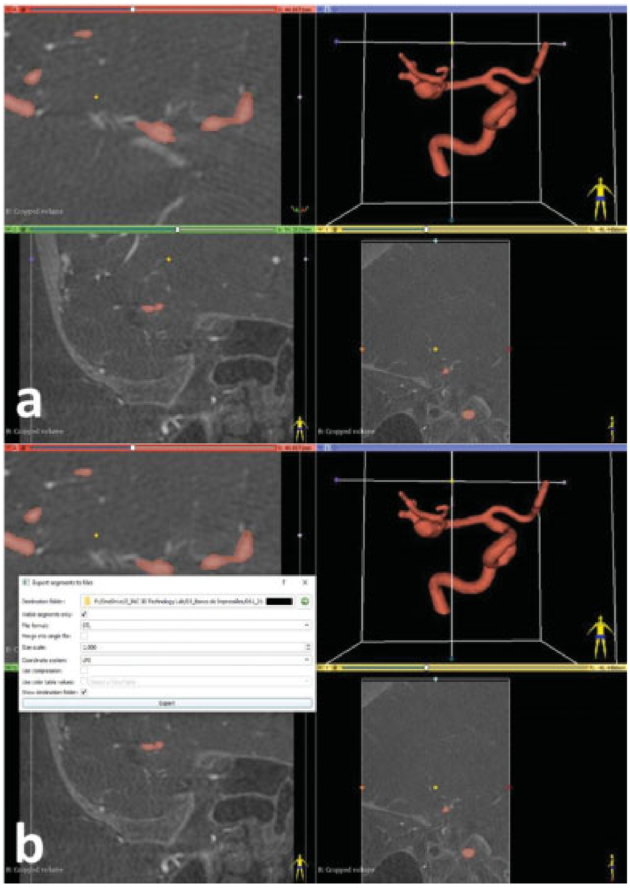


Fig. 1 (a) Creation of a CAD model of the object that is being projected; (b). Conversion of the CAD file into .STL extension.

4. Material jetting: a process in which droplets of build material are selectively deposited;
5. Powder bed fusion: when thermal energy selectively fuses regions of a powder bed;
6. Sheet lamination: a process in which sheets of material are bonded to form a part;

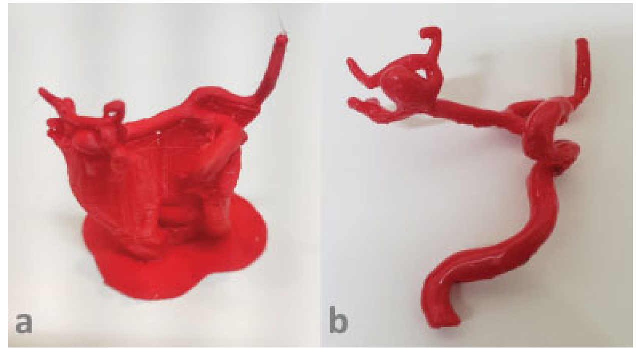


Fig. 3 (a and b) Cleaning and finishing of the model.

7. Vat photopolymerization: when a liquid photopolymer in a vat is selectively cured by light-activated polymerization.

Additive Manufacturing in Neurosurgery

Surgical procedures in neurosurgery can represent substantial challenges even for the most experienced surgeons, mainly in vascular and skull base surgeries. These challenges rise when handling lesions located inside or near the critical structures of the brain, or anatomically complex lesions.

Since its introduction in neurosurgery in 1999,[24] 3D printing has demonstrated its ability to aid in neurosurgical procedures. The comprehension of the brain structures is enhanced with the use of 3D biomodels before surgery. Moreover, 3D printing configures a promising opportunity for the preoperative training of the neurosurgeon. It is known that the excessive manipulation of intracranial nerves or vessels during the resection of a brain tumor, for instance, delays the surgery and constitutes a factor that can lead to neurological deficits, which, sometimes, are irreversible.[25]

Today, in surgical practice, the availability of an image-guided surgery configures a component in the development of surgical skills.[26] The virtual reality (VR) systems for surgical simulation demonstrate promising results.[27]

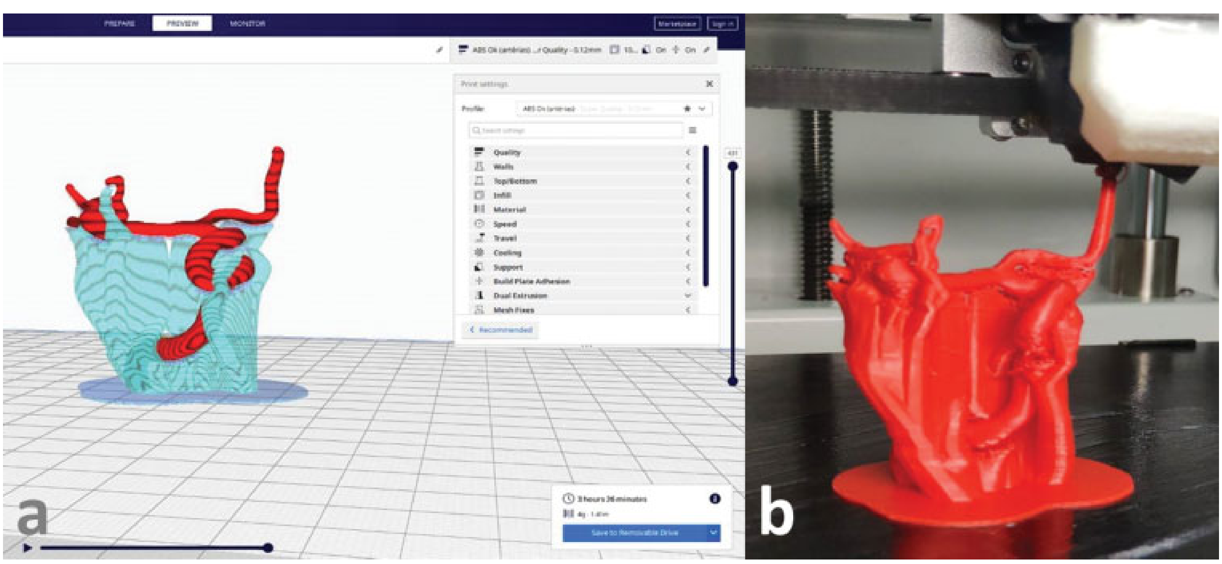


Fig. 2 (a) Decomposition of the .STL file into thin transversal layers. (b) Physical construction of the model, piling up one layer on another.

However, these systems are usually expensive, and supply only limited tactile feedback. In Brazil, the use of cadaver specimens it is still very restricted, since it depends on the availability of resources and biohazard issues. Studies in animals raise ethical questions and cannot always provide a realistic representation of the human anatomy.[10]

The projecting and manufacturing of anatomical biomodels are motivated by the need for realistic and reproductible models for surgical planning, training, and simulation. The development of 3D models has the potential to provide a series of advantages for neurosurgery, such as an educational perspective to both physicians and patients, and even to enable a surgical simulation.

Studies involving 3D printing in neurosurgery are concentrated on three main areas: (1) creation of anatomical tailor-made models for planning and training; (2) development of devices and materials for the treatment of neurosurgical diseases; and (3) biological implants for tissues engineering.[28]

Biomodels are extremely useful in several branches of neurosurgery. We can highlight the use in spinal, cerebrovascular, endovascular, neuro-oncological, neuropediatric, and functional surgeries.

Ideal guidelines for the acquisition of CT images were evaluated and determined that the acquired images should have a thickness of 2 mm, and this data was adapted for the creation of 3D models.[29,30]

However, with the advances in CT and 3D printer technologies, the acquired images have thinner slices (0.6 mm), as presented elsewhere by one of the authors (Leal A. G.) of the present article,[17] and can generate models with more details and precision.

Also, MRI was evaluated for 3D data acquisition, but the resulting models were of lower quality when compared with the biomodels derived from CT. However, when the brain is prototyped, MRI images are more suitable due to the low definition of CT for soft tissues.[31]

Biomodels of intracranial aneurysms (IAs) have been studied for preoperative planning and surgical training.[32–34] Some published studies reported that the biomodels were anatomically precise when compared with the real anatomy of the patient acquired through images of cerebral angiographies.[35–37] Among these studies, one of the authors of the present study (Leal A. G.) can be cited (►**Fig. 4**).[17]

It is known that one of the main difficulties during the microsurgical treatment of IAs consists in the appropriate choice of the clip to be used, due to anatomical variabilities and to the peculiarities of each aneurysm. It is also common knowledge that IAs present wide and/or complex necks and that surgical planning is essential[38] to avoid excessive manipulation of the intracranial vessels and an extended surgical time, which are factors that can predispose to intraoperative aneurismatic rupture.[39] Therefore, preoperative planning in touchable models that reproduce the surgical anatomy is enormously useful (►**Figure 5**).

Although published studies[40–42] have already demonstrated the usefulness of biomodels in the preoperative election of the surgical clip, studies with an objective evaluation of the effectiveness of 3D modelling for surgical planning and training are still lacking. This project was recently published by the authors of the present study (►**Fig. 6**). ►**Table 1** lists the experience of the main author of the present study (Leal A. G.) in the use of IAs models.[43]

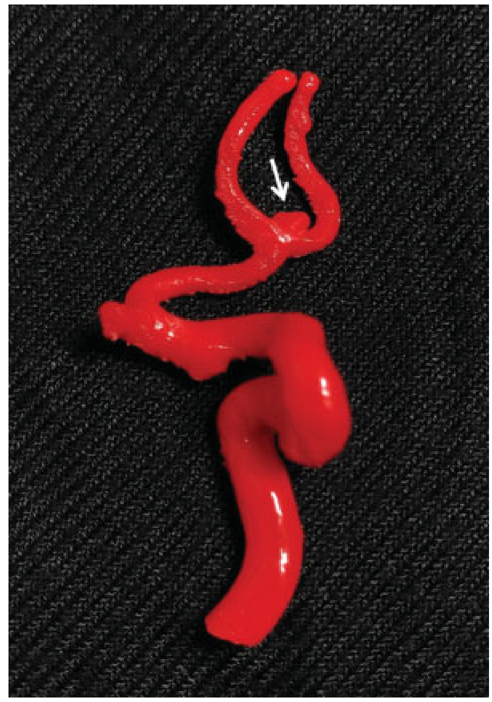


Fig. 4 Anterior communicating artery aneurysm (arrow) model.

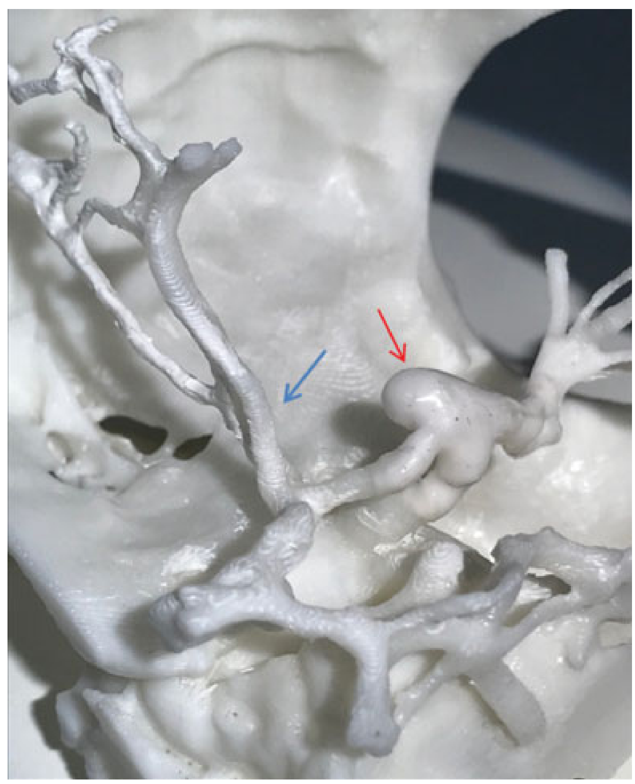


Fig. 5 Aneurysm model for preoperative election of the surgical clip. Flexible (red arrow) and hard (blue arrow) portions.

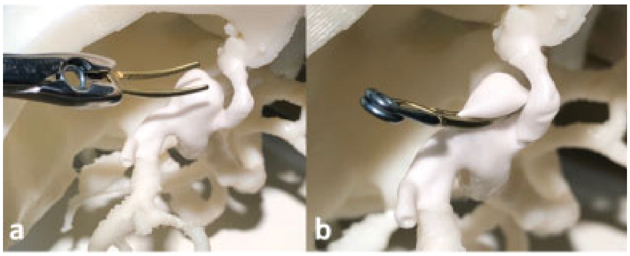


Fig. 6 Aneurysm model before (a) and after clip application (b).

Regarding cerebrovascular diseases, a study with 3D biomodels and arteriovenous malformations (AVMs) demonstrated that the intraoperative time was reduced, confirming that the printed models contributed to the surgical planning.[44] Additive manufacturing technology is used to manufacture 3D models of the AVM and to facilitate the preoperative conversation with the patient and to serve as medical education for young surgeons.[45,46]

Carotid endarterectomy (CE) has also entered the AM era. Before the advent of AM, CE depended on the patients'

Table 1 Experience of the main author in the use of intracranial aneurysms models[43]

Case	Age (years old)	Gender	IA location	IA size (*)
1	38	M	R ICA (Bifurcation)	7.3 × 5.1 mm
2	65	F	L MCA (Bifurcation)	3.6 × 3.9 mm
3	71	M	ACoA	4.3 × 3.4 mm
4	73	F	R ICA (Bifurcation)	3.3 × 4.5 mm
5	70	F	L ICA (Bifurcation)	5.9 × 5.6 mm
6	69	F	R ICA (Bifurcation)	7.6 × 3.9 mm
7	64	M	R ICA (Segment C7)	2.6 × 3.1 mm
8	63	F	L ICA (Bifurcation)	3.8 × 2.4 mm
9	55	F	R ICA (Bifurcation)	4.8 × 2.5 mm
10	67	F	R ICA (Segment C7)	1.3 × 2.0 mm
11	43	F	L ICA (Segment C4)	4.5 × 6.0 mm
12	66	F	L MCA (Bifurcation)	5.1 × 4.5 mm
13	54	F	MCA (Bifurcation)	4.9 × 4.4 mm
14	56	F	ACoA	4.1 × 2.1 mm
15	55	M	L MCA (Bifurcation)	2.4 × 2.8 mm
16	69	F	L ICA (Segment C7)	2.8 × 7.6 mm
17	71	M	ACoA	4.6 × 6.8 mm
18	50	F	R AChA	2.7 × 3.2 mm
19	63	M	L MCA (Bifurcation)	4.4 × 5.9 mm
20	74	F	ACoA	3.4 × 4.6 mm
21	66	F	R ICA (Segment C4)	7.4 × 15.7 mm
22	66	F	L ICA (Segment C4)	3.8 × 5.2 mm
23	39	F	R MCA (Bifurcation)	4.0 × 1.8 mm
24	66	F	L ICA (Bifurcation)	4.1 × 4.0 mm
25	66	F	ACoA	4.1 × 2.8 mm
26	74	F	ACoA	4.3 × 3.7 mm
27	62	F	R ICA (Segment C6)	3.5 × 6.3 mm
28	51	F	R MCA (Bifurcation)	3.0 × 3.1 mm
29	57	F	R MCA (Bifurcation)	6.3 × 7.7 mm

Abbreviations: AchA, anterior choroidal artery; ACoA, anterior communicating artery; CMA, middle cerebral artery; IA, intracranial aneurysm; ICA, internal carotid artery; L, left; R, right.

surgical exposition. This procedure demands an experienced surgeon with a very low incidence of complications. The high-risk nature of this procedure, as well as the decline in the number of these surgeries performed annually due to the advent of the endovascular technique, created a gap in the training of young neurosurgeons and vascular surgeons. Additive manufactured models for the simulation of CE have demonstrated that they provide comprehensive training and allow the residents to obtain skills before operating on a patient.[47]

In the same way, biomodels were also validated for preoperative planning in the endovascular treatment of vascular diseases with microcatheter molding[48,49] and in the endovascular treatment of intracranial arterial stenosis.[50]

Three-dimensional models were used in brain tumors to evaluate the association between healthy and adjacent neoplastic tissues and to help delineating the resection borders. Three-dimensional printing of brain tumors uses the fusion of CT and MRI images as its basis, improving anatomical comprehension.

Currently, neuro-oncological preoperative planning is based on imaging exams, mainly on MRI, since it provides more detailed images of the brain tissues. The use of perfusion techniques and tractography can also provide important details for the choice of the approach to be used by the neurosurgeon. In the same way, stereotaxis and neuronavigation came to facilitate pre- and intraoperative planning, since they provide the location of intracranial structures, in real time, on the previously acquired imaging exams.[51] However, even if these images supply important details for the preoperative planning, some difficulties still persist in the differentiation between tumor lesions and the underlying cerebral structures. Additive manufacturing technology allowed the MRI data to be transduced into tailor-made biomodels describing the relationship between tumor, vasculature, and cerebral tissue, facilitating the understanding and, consequently, resulting in the planning of the most effective treatment.[52]

The validity of this technique was confirmed by reports of preoperative planning using tractography in 3D models, mainly when used in complex tumor resection surgeries, such those of gliomas. Diffuse low-grade gliomas are infiltrative tumors that pervade cortical and subcortical structures in the brain. The understanding of the anatomical relationships, case by case, is fundamental for a successful neurosurgical therapy. Additive manufacturing based on tractography images can improve the skills of the surgeon to plan and to treat these types of lesions. This process can reduce surgical time and contributes to increased safety to the patient in tumor resection surgeries when nerve tracts are involved or are part of the tumor approach.[53]

Skull base tumors surgeries also benefit from the use of AM due to the extreme difficulty of the surgical approach and to the anatomical complexity.[54,55] In these lesions, deeper areas are not visible in prototyped models manufactured with opaque materials. Additive manufacturing techniques were refined through the years and, now, translucent materials can be printed providing a better visualization of the structures involved with the lesion.[56]

The use of 3D printing has brought the development of simulators created from the construction of the skull, with all its components, using a variety of materials with consistency and density very close to reality. Polyjet technology has become the preferred method to print devices for this purpose.[57]

One of the simplest indications of the AM technology was in the development of molds for the reconstruction of cranial bone defects. In neurosurgery, the need for large craniectomies for cerebral decompression in cases of traumas or extensive ischemic strokes when the edema can cause expressive increase of the intracranial pressure is well-known. As a routine, after the acute phase, the closure of the bone defect (cranioplasty) is performed with metilmetacrilate, which is manipulated by the surgeon intraoperatively.[58–61] However, the cranioplasty of large bone defects does not always result in suitable esthetic outcomes. Therefore, 3D tailor-made molds for cranioplasty are very useful.

Recently, 3D printing has also been used in pediatric neurosurgery, as in the case of surgical correction of the meningoencephalocele. These are rare diseases, and few pediatric neurosurgeons are comfortable with performing this kind of surgery. In this context, the use of biomodels is fundamental to establish reliable and safe surgical techniques for each case. The anatomical relationship between the brain and the skull can be represented by biomodels, clearly demonstrating the involved lesions. Additive manufacturing technology allows the previous planning of the surgical approach and the development of strategies to deal with several intraoperative high-risk. Three-dimensional printed models offer not only a better view of the planning process, but also provide substantial information to enhance the precision of surgical reconstruction in meningoencephalocele surgeries.[62]

In pediatric neurosurgery, a short anesthetic time, as well as reduced radiological exposure and blood loss, are very important. It was observed that, with the use of 3D models, the duration of surgery was reduced when compared with procedures that did not use this technology.[63]

Like surgical correction of meningoencephalocele, surgeries for skull reconstruction due to craniosynostosis also benefit from manufactured models (►**Fig. 7**). Frequently, craniosynostosis is a complex disease, usually involving orbital and facial bones along with cranial deformity. Sometimes, surgical treatment is challenging, and it almost always requires a multidisciplinary approach, with association of a neurosurgeon and a plastic surgeon. The complexity of this surgery lies in the multiple possibilities of reconstructions, which would benefit from pre- and intraoperative definitions of biometrics and esthetics. Three-dimensional printing transforms the virtual planning into anatomical replicas of the cranium, which can be manipulated and fitted, as a jigsaw puzzle, to find the best reconstruction form.[64,65]

Fig. 7 Craniostenosis model.

Surgeries for resection and cranial reconstruction due to fibrous dysplasia, a benign pathological development of the bone, can also have their planning aided by 3D models.[66]

Another common neurosurgical procedure of interest for the development of simulation using AM is endoscopic third-ventriculostomy (ETV).

Endoscopic third-ventriculostomy and intraventricular biopsy surgeries are procedures whose training is particularly complicated due to the relatively small number of cases and to the involved techniques that are different from those used in conventional neurosurgery. Three-dimensional printed models can simulate the scenario for neuroendoscopic procedures, allowing safe and effective teaching in a realistic and repetitive way.[67] An important advance in some of these simulation devices is the addition of a ventricular system full of liquid that can provide variable ventricular pressures.[68]

Endoscopic transnasal surgeries have also been another important and pioneering area in the integration of 3D printing in the development of surgical simulation. A physical simulation can reproduce the complex anatomy of the anterior fossa and provide useful ways to apprehend the necessary abilities in a safe and effective scenario.[69,70]

Using implantable electrodes, the surgeon evaluates the epileptogenic cortical area and can also have the location of the implant defined through 3D models.[71]

In the literature, a growing number of papers describe the use of 3D printing for spine surgeries in the last years. A recent systematic review on the applications of AM in spine surgery found > 2,400 articles on the subject. It concluded that 3D printing is rapidly becoming intimately integrated with surgical interventions in the spine. Currently, it is used for surgical planning and intraoperative guidance, besides aiding the production of tailor-made prostheses. The technology allows the reduction of the surgical time and better surgical results (►**Fig. 8**).[72–74]

Clinical benefits such as improved diagnosis, reduction of the time of fluoroscopy, reduction of the surgical time, decrease of intraoperative bleeding, better communication of the surgical team, and a lower index of malpositioning of screws were reported.[8,74,75]

Fig. 8 Spine model.

Pedicular screws are routine for spine neurosurgeons, since they are the most effective way to stabilize the vertebrae.[76] However, the traditional implantation techniques are associated with many problems and present a high risk of violation of the pedicle, with the possibility of causing potentially fatal neurovascular damages.[77]

Three-dimensional guidance can offer an alternative, simple, convenient, and low-cost way to improve the precision of the positioning of pedicular screws.

Currently, one of the most important applications of 3D printing in spine surgery is the capacity to manufacture the tailor-made implants for the patient. First, an imaging exam is performed and a specific prosthesis for the patient can be prototyped. Despite its innovation, this process is still very expensive.[78,79]

Three-dimensional printing with a material based on plaster was used to create n touchable anatomical model of the lumbosacral spine according to the CT image. These models can be used to perform a variety of procedures, including interventions in pain management, such as epidural and nerve roots blockades, facets injections, and blood patching in cases of cerebrospinal fluid (CSF) hypotension.[80]

Craniovertebral joint anomalies can be very difficult to be treated surgically. The preoperative information on bone anomalies, the pathway of the vertebral arteries, the size of bone pedicles, and the location of the transverse foramens are important for the surgeons. The sizes of the plates and screws to be used, as well as the angle of screw insertion, can be calculated based on the data of the models.[81,82]

Also, this technique can be applied in the treatment of atlantoaxial basilar invagination and displacement. Three-dimensional printing can give detailed information about the abnormalities of the bone structure and of the vertebral artery pathway. It is useful to configure the surgery strategy and to project the access point and the pathway of the screw, consequently avoiding lesions of the vertebral artery and of the bone marrow.[83]

Neuromodulation techniques can provide an analgesic treatment for patients with chronic pain. Sometimes, these treatment techniques can fail due to a mistake in the access to the peridural space. Three-dimensional printing can provide additional information to improve the odds of access when the anatomy is distorted.[84]

3D Printing in Neurological Clinical Practice

While 3D printing is intuitively attractive, several barriers exist for its widespread implementation. The process of construction of the model can be partially automated, but for clinical use, some care should be taken during this process. The final quality of the biomodels depends on the quality of the acquired image from cerebral imaging exams. A careful analysis is required when segmentation is made manually, due to the complexity, the reduced sizes, and irregular pathways of the brain structures. The specialized manipulation of the segmentation programs by AM, imaging, 3D files generation technicians in is of extreme importance. Technical knowledge of operating systems and segmentation software is of crucial importance.

The final quality of the biomodel depends on the several stages of its production, from the acquisition of images through CT and MRI to the actual final printing. The quality of the equipment used also influences the final result of the pieces. The largest discrepancies of the production of biomodels correspond to their dimensions, which are related to the thickness of each printed slice. Taft et al.[85] described that the absolute magnitude of error was small and within the tolerance range generally accepted for the treatment of a patient. Therefore, the stages of quality control or the validation of the model are crucial when the printed models in 3D are used for the sizing of the device. A survey of evaluations of the models should always be considered, for instance, by means of the evaluation of the images of the biomodels with the same imaging techniques from which they were originated. In the case of IA biomodels, the evaluation can be processed by comparing the measurements of the neck, of the height of the aneurysm, and of the diameter of the involved cerebral arteries.[43]

Also, another important factor is the high cost of 3D printers, in addition to the fact that almost all of them still depend on technicians for handling. The materials used to build the object also involve high prices and are difficult to be obtained.

One of the main limitations of AM is that the current technologies cannot print directly ultramalleable materials, such as human cerebral tissues. A new method was proposed to create a 3D model – both anatomical and tactile – of the human brain based on MRI and CT images. The production process consists of three stages and uses the solid 3D model of the brain, followed by the construction of a negative silicon mold of the first model and using it as a model for the creation of a piece produced with a jelly that resembles the original consistence of the human brain.[86,87]

The production of tailor-made biomodels, which initiates with the acquisition of the images and ends with the impression of the piece, is time-consuming. The time required to produce a model varies, on average, from a few to 12 hours, depending on the size of the printed object, and can take up to 24 hours if the desired object is a complete skull. In this context, the use of biomodels is only possible in elective cases, and their use in emergencies remains very restricted.[16,17]

Only one paper described the use of emergency 3D printing in neurosurgery. The authors developed a method to produce solid models of cerebral aneurysms, with a shorter time of impression than those of the conventional methods, using a compact 3D printer with acrylonitrile-butadiene-styrene (ABS) resin.[88]

Three-dimensional printers are developing quickly; consequently, due to their popularity, their cost is decreasing. The generation of 3D files, such as the files with '.STL' extension derived from Digital Imaging and Communications in Medicine (DICOM) data, is being recognized as a clinical need, and this ability is being introduced in the software of several imaging diagnosis medical equipment. Currently, CT and MRI equipment that automatically generate '.STL' files already exist, enabling the presentation of the results of the exams both in 2D and in 3D printing.

Tailor-made production of biomaterials is already a fact. However, the envisioned future is the printing of human tissues. Bioprinting has achieved thin layers of tissues that are biologically active and can be used for pharmaceutical tests. A promising development area is 3D bioprinting of neurovascular units and the contribution of the different types of cells for the neurovascular function. Also, dysfunctions can be studied at the molecular and cellular levels.[20,89–92]

Conclusions

Additive manufacturing in neurosurgery with educational and clinical purposes is highly promising and will probably widen its use and application. Although challenges still exist due to the cost of production of 3D printing, as well as to the limitations in the available materials, these current barriers shall be overcome with new research and technological progress.

Until now, 3D printing has focused on the increase and demonstration of the applicability of this technology, showing its usefulness in preoperative planning and training, as well as in the acquisition of neurosurgical skills, besides in the improvement of the education of physicians and patients.

To establish the use of AM in the neurosurgical practice, further studies focusing on demonstrable clinical results and on suiting them to the use of this technique will be needed. For instance, the choice of surgical materials in preoperative planning can avoid unnecessary expenses and reduce manipulation of the cerebral structures. Given the path of the 3D printing technology and its usefulness already demonstrated in multiple clinical scenarios, its widespread application in neurosurgery, in the future, seems to be inevitable.

Additive manufacturing provides an exclusive way for direct replication of the specific pathologies of the patient. It can identify the anatomical variation and provide a way for rapid construction of training models, allowing the medical resident and the experienced neurosurgeon to practice the surgical steps before the operation.

As a future perspective, it is necessary to move beyond the current state of 3D biomodels that represent actual 3D anatomical reconstructions. These models still do not provide simulations of more delicate maneuvers, which involve real blood consequences. The use of materials with a consistency similar those of the cerebral and spinal tissues, as well as the simulation of bleeding, should be developed. Therefore, the next steps must overcome these challenges.

Contributions of the Authors

Leal A. G.: Conception and design, data analysis and interpretation, drafting of the manuscript; Ramina R.: Critical revision of the manuscript, reading and approval of the final manuscript; Aguiar P. H. P.: critical revision of the manuscript, reading and approval of the final manuscript; Souza M. A.: Research supervision and critical revision of the manuscript, reading and approval of the final manuscript; Fernandes B. L.: critical revision of the manuscript, reading and approval of the final manuscript; Nohama P.: research supervision and critical revision of the manuscript, reading and approval of the final manuscript.

Conflict of Interests

The authors have no conflict of interests to declare.

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