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The Role of Three-dimensional Printer Modeling in Preoperative Planning of Brain Tumor and Aneurysm Surgery

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ABSTRACT

Introduction: The three-dimensional (3D) modeling technique, which is one of the latest technologies, has been applied in neurosurgical practice. The surgeon's knowledge and experience are crucial for the success of the surgical treatment of brain tumors and brain aneurysms. This study emphasizes that the contribution to successful surgery is by ensuring that the surgeon is fully oriented before and during the operation.

Methods: The study included five patients with brain tumors and five patients with hemorrhagic aneurysm, which were diagnosed between May 2021 and November 2022. Both patient groups were evaluated retrospectively, and all operations were performed by the same experienced surgeon. 3D models of the patients were prepared using a computer program. These models were examined by the operating surgeon during the preoperative period and were sterilized and used as a guide during the operation.

Results: The patients were divided into two groups, one composed of five patients undergoing surgery with the diagnosis of a tumor and the other composed of five patients undergoing surgery due to a ruptured aneurysm. All operations were performed by the same experienced surgeon. Successful clipping was performed in all patients with ruptured aneurysms.

Conclusion: Surgeons have been analyzing complex neuroanatomy data using the 3D modeling technique before surgery. The preoperative simulation improved the surgeon's command of the field and orientation to the surgery. These findings suggest that 3D modeling will positively affect a successful surgical operation and the management of complications that may occur. More prospective randomized studies are needed to confirm these findings.

Keywords: Three-dimensional printing, aneurysm, intracranial tumor

Introduction

Since its introduction in the 1980s, three-dimensional (3D) printing has birthed a new era of rapid prototyping (1). Realistic 3D modeling has been used in preoperative planning, resident education, and the testing and development of new technologies for endovascular and open surgery for cerebrovascular diseases (2,3).

The use of 3D printing in neurosurgery has led to significant developments. Since the importance of complex surgical anatomy affects surgical success, 3D printing has been applied in clinical practice as an advanced neuroimaging method. This technology has enabled a noninvasive visualization of the patient's pathology and complex neuroanatomical structures for both diagnostic and therapeutic purposes (4).

Owing to this technology, complex anatomical structures can be reconstructed from 3D volumes. The physical models created as a simulator can be used for surgical planning by the attending surgeon and for the assistance in education (5).

It is critical to have the necessary anatomical knowledge in surgical planning and to develop a strategy for a successful surgery. Until today, these strategies were made on the basis of cadaver studies and information in neuroanatomy textbooks. The development of 3D modeling technology has created an identical simulation and provided the opportunity to present the surgical anatomy knowledge to the neurosurgeon perfectly. We think that the 3D modeling technique will increase the success of the surgery in the near future and will be used as an important tool in the training of neurosurgeons.

In our clinic, we used 3D printing modeling technique in our patients who underwent surgical procedures for cranial tumors or aneurysms. This study explains in detail the 3D models we used in the preoperative planning phase and our intraoperative experiences for treating these patients.

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Methods

Ten patients who underwent surgery in our clinic with the diagnosis of brain tumor and intracranial aneurysm between May 2021 and November 2022 were included in this study. The contribution of the use of preoperative 3D models during surgery was analyzed retrospectively.

In the neuroanatomy laboratory of our clinic, 3D modeling studies started before May 2021. Developing the modeling technique, optimizing the printing time and low cost targets have emerged because of many years of work and this technology has been put into the service of our patients. Today, this method has been further developed in our clinic and it has started to be applied in complex spine stabilization and spine tumors surgeries. It is aimed to contribute to the literature by sharing our experience in this technology, which we have been working on and developed for many years. This technique continues to be routinely used and developed by the same surgeon who performed these surgeries.

All patients reviewed and signed the informed consent forms in detail. Approval from the İzmir Katip Çelebi University Ethical Committee was granted (approval number: 0598, date: 22.12.2022). Data regarding the demographics of the patients, location of the tumor, symptoms upon admission, pathology results, the duration of the operation, duration of stay, presence of complications, and Karnofsky performance score (KPS) were evaluated.

3D Model Creation

The computed tomography (CT) and magnetic resonance imaging (MRI) data were obtained in Digital Images and Communications in Medicine (DICOM) format, enabling the formation of an interface between devices in favor of creating a solid model. The RadiAnt DICOM Viewer (Medixant, Poznan) application was used to differentiate between the tumoral tissue, skull base, and vascular neuroanatomy. The data of the tumoral tissue, skull base, and vascular structures were converted into a 3D model and exported as ".stl" files. 3D STL models were obtained from the Radiant DICOM Viewer and meshed again using the Meshmixer™ (Autodesk, San Rafael, U.S.A.) software. The models prepared for 3D printing were exported and sliced using the Cura (Ultimaker, Geldermalsen, The Netherlands) software and then the Gcodes were created (Figure 1) (6).

The PLA filament of 2.85 millimeters was used during the printing process in accordance with the manufacturer's recommendations. The process settings were standardized as follows: extruder temperature at 215 °C, room temperature at 24 °C, primary layer height of 0.1 mm, and filling rate of 20%. The 3D models were printed on a 1:1 scale (7).

The skull base model and 3D tumor model were created separately in different sessions. Thin section (0.3 mm) brain tomography data were used for modeling the skull base, whereas the thin section (0.5 mm) cranial MRI data were used to print the tumor tissue. The 3D tumor model was adhered to the skull base model using a special model glue and the tumor model was colored with special model paints.

Brain aneurysm 3D models were prepared in a single session using thin section (0.3 mm) cranial CT angiography data, and then the vascular structures were colored using special model paints.

A professional photography studio was created to obtain high-quality 3D images of each 3D model by combining multiple focus images using Canon EOS 2000D (Tokyo, Japan).

Thin section tomography data are used in the printing of bone tissue and vascular structures while creating the 3D model. Thin section t2 flair MRI sequence data are used for printing tissues such as tumors. The required print quality could not be achieved in non-thin section tomography and t2 flair MRI sequence data. It is technically possible to model every patient whose necessary data can be obtained. The main difficulty is that the entire modeling cannot be done in a single print. The necessary data must be printed separately and then joined with suitable adhesives. The aim of all this 3D modeling technique is to increase the surgical neuroanatomical orientation of the neurosurgeon and to reduce the complications that may develop.

Preoperative planning was performed based on the patient's history and imaging, individualized 3D printed tumor, skull base, and vascular neuroanatomy models. The models were sterilized and taken to the operation theater for intraoperative navigational purposes. After the operations were performed, the material quality, potential benefits on the preoperative planning, impact on the prediction of complications, and usefulness for the educational purposes of the 3D printed models were evaluated.

Statistical Analysis

The Statistical Package for Social Sciences Version 22.0 (SPSS, Chicago, IL, USA) software was used for statistical analysis. The mean, median, and standard deviation values were also obtained.

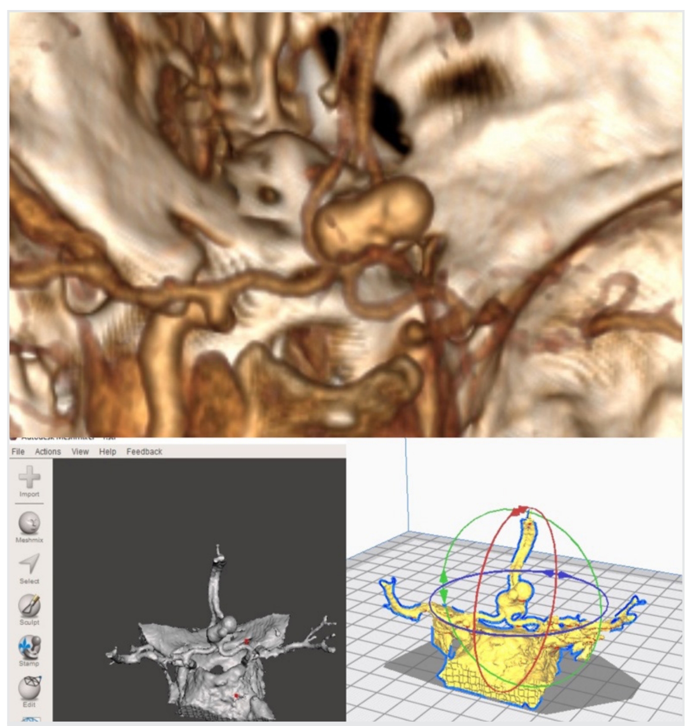

Figure 1. Screen images from computer programs used for 3D aneurysm modeling of a patient with acom aneurysm

Results

Five patients with a diagnosis of brain tumor and five patients with a bleeding aneurysm were included in our study. 3D models of all patients were prepared in the preoperative period, and the surgeon had the opportunity to work on 3D models in the neuroanatomy laboratory before surgery (Figures 2-4). Both patient groups were evaluated within themselves.

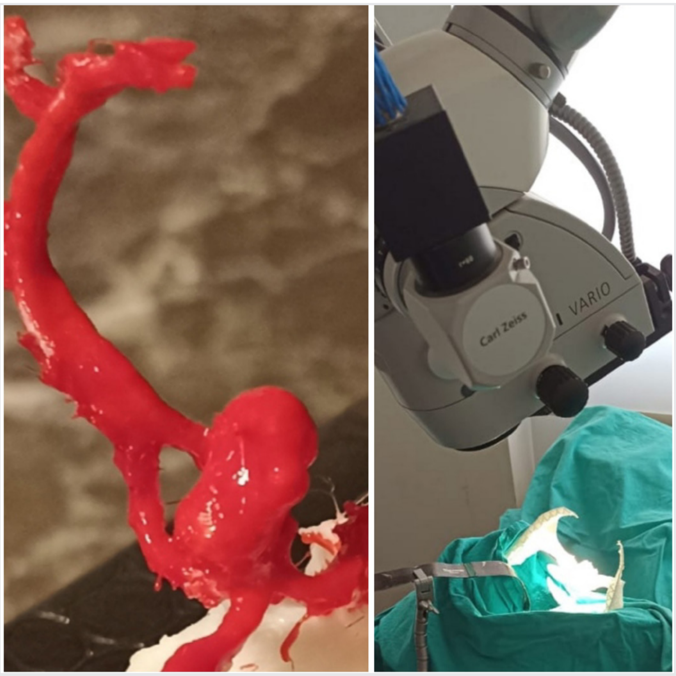

Figure 2. Aneurysm 3D model and training under a surgical microscope in a neuroanatomy laboratory

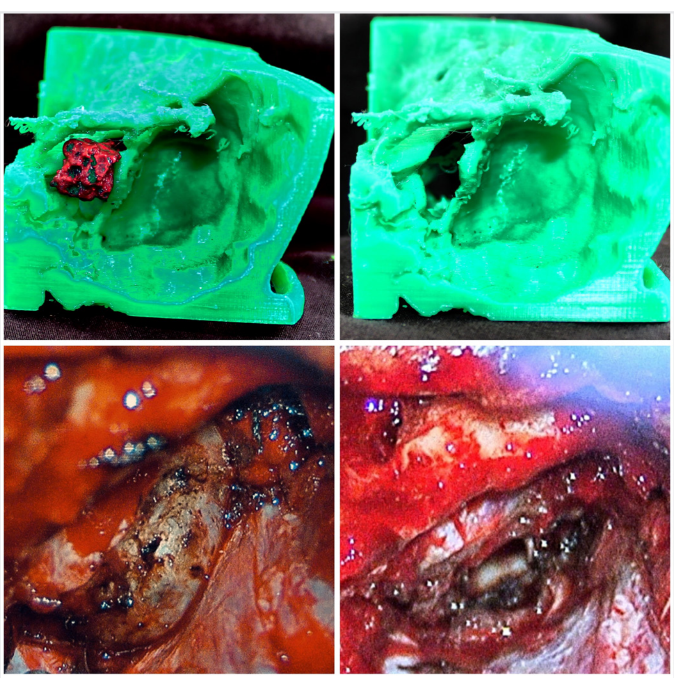

Figure 3. Presentation of the created 3D model of the patient with a retro-orbital tumor with intraoperative image

Tumor Group (Table 1)

The mean age of five patients was 57.2±24.47 (range 22-84), in which 40 % (n=2) of the patients were female and 60% (n=3) male. The mean duration of hospital stay was 7.8±0.83 days. The presenting symptoms were headache (40%), dizziness (20%), hearing loss (20%), and vomiting (20%). Three patients had tumors in the posterior fossa. The other patients' tumors were located on the anterior skull base. Three patients (60%) underwent total resection, one patient gross total resection (20%), and one patient (20%) subtotal resection. The mean duration of operation was 202±35.63 minutes. The pathology results were as follows: two (40%) meningiomas, one (20%) hemangioblastoma, one (20%) neuroendocrine metastasis, and one (20%) schwannoma. One patient experienced temporary oculomotor paralysis and was treated with I.V. steroids for 7 days. The patient also received additional oral steroid treatment after discharge. The mean postoperative KPS was 88±16.43. The KPS of the patients at the time of discharge was as follows: 100 (40%, n=2), 90 (40%, n=2), and 60 (20%, n=1).

Ruptured Aneurysm Group (Table 2)

The mean age of five patients was 46±15.08. 40% (n=2) of the patients were female and 60% (n=3) male. All patients had high bleeding stages and were in a severe coma, and their Glasgow Coma scale (GCS) were below 8. The mean GCS was 6.2±1.48. Four patients (80%) had Fisher grade 4/Yasargil grade 4, whereas one patient (20%) had Fisher grade 3/ Yasargil grade 5. While the aneurysm localization of three patients (60%) was in the middle cerebral artery, two patients (40%) were in the anterior communicating artery. The mean size of the aneurysm was 11.9±5.89 mm, and 4 patients (80%) had intraparenchymal hematomas opening into the ventricle. The mean hematoma volumes were 28.59±18.4 cc. The mean midline shift in the patient' brain tomography was 7.66±4.49

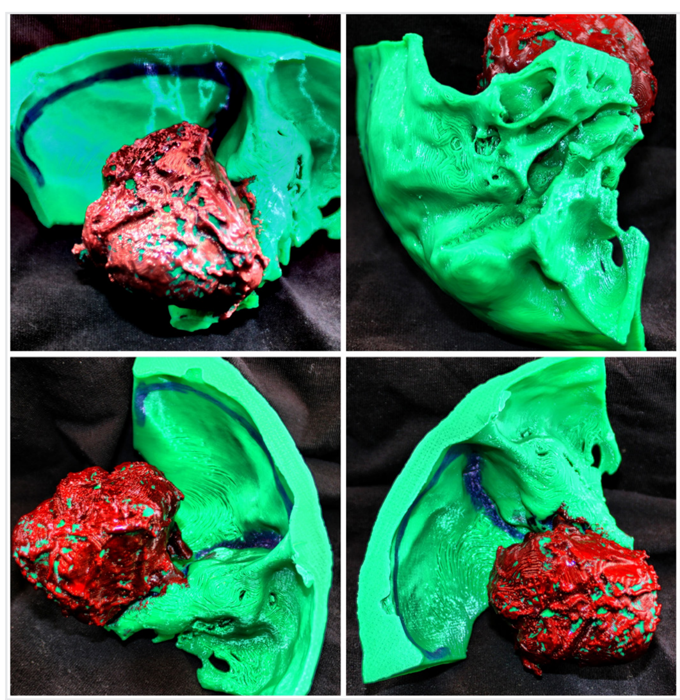

Figure 4. Preoperative 3D model of a patient with vestibular Schwannoma who underwent cerebellopontine angle tumor surgery

mm. Decompressive craniotomy, external ventricular drainage, and clipping were successfully performed in all patients. The mean duration of operation was 188±19.23 minutes. One patient was discharged with a KPS of 90. Severe vasospasm developed in four patients postoperatively. While three patients died, one patient was discharged with a KPS of 20 in a vegetative state. In the high-stage ruptured aneurysm group, the mean hospital stay was 20.6±14.94 days.

Discussion

Okonogi et al. (8) created 3D-printed anterior clinoidectomy models in patients with sphenoid wing meningiomas and giant ophthalmic segment aneurysms. They performed anterior clinoid drilling on the model preoperatively and considered it beneficial for surgical training (8). We also performed drilling studies on the models we created in our study and observed the benefits of these drills for resident training. Particularly in the 3D model of our patient with a retro-orbital mass lesion, the relationship of the tumor with the superior orbital fissure positively affected the planning of our surgical strategy.

Oishi et al. (9) simulated deep intracranial tumors (meningioma, schwannoma, epidermoid tumor, etc.) in 12 patients in a 3D virtual environment. They then decided on surgical strategies by creating 3D

Table 1. Demographic data, as well as location and pathology of the tumors and complications are shown on the table

No	1	2	3	4	5
Age	84	22	48	76	56
Gender	Male	Female	Female	Male	Male
Radiology	Cerebellum	Cerebellopontine	Retro-orbital	Cerebellum	Olfactory groove
Size (mm)	55*56*44	40*35*30	20*12*15	40*41*35	25*30*19
Symptom	Dizziness	Hearing loss	Headache	Vomitting	Headache
Sign	Neurological deficit	Neurological deficit	Exophthalmus	Neurological deficit	None
Surgery	Total resection	Subtotal resection	Total resection	Gross total resection	Total resection
Surgery time (min)	230	210	170	240	160
Pathology	Meningioma	Schwannoma	Hemangioblastoma	Neuroendocrine metastasis	Meningioma
Complication	None	None	Temporary oculomotor paralysis	None	None
Hospital stay (day)	7	9	8	8	7
Preoperative KPS	100	90	100	70	100
KPS on discharge	100	90	90	60	100

KPS: Karnofsky performance score; min: Minimum

Table 2. Demographic and morphological data, as well as complications of the aneurysm surgery are shown on the table

No	1	2	3	4	5
Age	54	51	23	62	40
Gender	Male	Male	Female	Female	Male
Aneurysm	MCA	Acom	Acom	MCA	MCA
Size (mm)	15	12	6,5	6	20
Parenchymal hemorrhage size (mm)	20*20*25	40*45*29	none	42*60*39	49*41*34
Shift (mm)	3,5	8,6	2,5	12,5	11,2
Intraventricular hemorrhage	+	+	-	+	+
SAH	Fischer grade 4 Yaşargil grade 4	Fischer grade 4 Yaşargil grade 4	Fischer grade 3 Yaşargil grade 5	Fischer grade 4 Yaşargil grade 4	Fischer grade 4 Yaşargil grade 4
GCS	6	7	4	8	6
Surgery	Decompressive craniotomy + succesfully clipping	Decompressive craniotomy + succesfully clipping	Decompressive craniotomy + succesfully clipping	Decompressive craniotomy + succesfully clipping	Decompressive craniotomy + succesfully clipping
Surgery time (min)	200	180	190	210	160
Complication	Vasospasm	None	Vasospasm	Vasospasm	Vasospasm
Hospital stay (day)	16	15	10	15	47
Outcome	Exitus	Dischargered	Exitus	Exitus	Dischargered
KPS on discharge	-	90	-	-	20

MCA: Middle cerebral artery; KPS: Karnofsky performance score; GCS: Glasgow Coma scale; SAH: Subarachnoid haemorrhage anatomical models. In our study, we created surgical strategies based on such models.

Lan et al. (10) created preoperative 3D models for aneurysms and highly vascular tumors. They discussed the optimal preoperative surgical approach and the relationship of the aneurysm or tumor with the calvarium. They emphasized that young neurosurgeons would benefit from models, especially in cases with complex anatomy (10). In our study, 3D models of the aneurysms positively affected the surgical strategy. Aneurysm clipping was successful in all our aneurysm patients. It was observed that working on the 3D model contributed to the success of the surgery.

Van de Belt et al. (11) used 3D-printed models of glial tumors to provide sufficient information to the patients. They stated that the patients had a better understanding of their diseases with the help of 3D printed models. It was also noted that the patients were more confident in deciding on the treatment options offered to them (11). In our study, the 3D printed models were presented to patients and their relatives and were used to guide them while explaining the treatment of the disease.

Lin et al. (12) created a 3D model of two patients with a sellar tumor and one patient with acoustic neurinoma and compared the shape of the tumors intraoperatively. The relationship of the tumor with the sphenoid sinus, hypophyseal fossa, cerebellopontine angle, and main arteries is presented in 3D printed models. They emphasized the potential benefits of 3D modeling in neurosurgery education, while stating that cranial nerves would not be suitable for modeling (12). In our study, the nerve modeling of a patient with a corner tumor could not be performed clearly in 3D modeling, but the complex anatomy of the tumor in brainstem localization was clearly demonstrated. The 3D model has clearly made a positive contribution to the surgical treatment of the patient's surgery and resident education.

Damon explained in detail the 3D modeling of tumors and the printing technique (13). We successfully applied this technique in our study.

Thawani et al. (14) showed a relationship between low-grade glial tumors and white matter fibers on a 3D model. However, we did not perform white matter modeling in this study.

In another study, Thawani et al. (3) modeled arteriovenous malformations (AVM), feeding arteries, and drainage veins by printing them separately preoperatively. However, only aneurysm models were created in our study.

Weinstock et al. (15) produced monochrome models for patient and resident education. Uzunoglu et al. (7) emphasized the positive contribution of preoperative 3D models for successful surgery in 15 patients operated for an AVM.

Anderson et al. (16) created 3D models of ten aneurysms and compared the aneurysm diameter measurements with those measured by digital subtraction angiography (DSA), indicating no significant difference. Kondo et al. (17) analyzed the length, thickness, and diameter of the aneurysm on 22 aneurysm models and found no significant difference. Mashiko et al. (18) evaluated DSA and intraoperative appearance on 3D models of 20 aneurysms. They reported that the modeling was realistic and consistent. Namba et al. (19) compared 3D models of ten aneurysms with DSA and reported no inconsistencies. Furthermore, Wurm et al. (20) compared 13 aneurysm models intraoperatively and reported no inconsistencies.

It will take time for new technologies and developed techniques to be accepted in the medical field. New materials and different techniques continue to be introduced about the 3D modeling technique. As limits continue to be exceeded, 3D modeling may become routine in clinical use. To now, experience needs to be accumulated and developed to meet the high expectations in the field of neurosurgery (21).

All these studies suggest that 3D modeling is a safe technique and is anatomically consistent with reality. When we evaluated the radiologic measurements and intraoperative observations of our patients in our study, we observed that the 3D models we created were exactly compatible with actual pathology and showed no inconsistencies.

Study Limitations

Desired quality could not be achieved in the modeling of patients with CT and MRI sections over 1 cm. Therefore, these patients were excluded from the study.

Conclusion

Surgeons have been analyzing complex neuroanatomy data in detail with the use of 3D modeling before surgery. The preoperative simulation improved the surgeon's command of the field and their orientation to the surgery. Particularly in brain stem localization and during operations, in which the surgeon encounters technical challenges, such as clipping of a bleeding aneurysm, the benefit of 3D models has been confirmed. The difficulty in clipping a ruptured aneurysm accompanied by increased intracranial pressure, hematoma, and extensive subarachnoid hemorrhage, termed as angry brain, was overcome with improved orientation to the surgical field conferred by 3D models. Successful clipping was achieved in all patients. All these findings suggest that the use of preoperatively designed 3D models can result in a successful surgical operation and facilitate the management of complications that may occur.

Ethics Committee Approval: Approval from the İzmir Katip Çelebi University Ethical Committee was granted (approval number: 0598, date: 22.12.2022).

Informed Consent: All patients reviewed and signed the informed consent forms in detail.

Peer-review: Externally peer reviewed.

Authorship Contributions

Surgical and Medical Practices: M.A., G.G.; Concept: M.A.; Design: G.G.; Data Collection or Processing: M.A., G.G.; Analysis or Interpretation: M.A.; Literature Search: G.G.; Writing: G.G.

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