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Three-dimensional model printing for surgery on arteriovenous malformations

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Abstract

Aim: Surgery for intracranial complex vascular malformations can be quite exigent and involves considerable preoperative planning. Here, we present the advantages of using three-dimensional (3D) printed models as a preoperative investigational modality. **Material and Methods:** 3D printed models were made from thin-slice computed tomography (CT) angiography scans of 6 patients with arteriovenous malformations over an18-month period from August 2015 to December 2016. The locations of the arteriovenous malformations were in the Sylvian fissure in 1 patient, posterior frontal region in 2 patients, subfrontal region in 1 patient, and parietal region in 2 patients. The CT angiography was performed on a 64-slice CT scanner. Thin-slice axial CT sections were acquired and a volume file was created of the arteriovenous malformation and the required skull bones. The file was then transferred to the 3D printer for creating the model. **Results:** The model depicted the precise nature of the compactness and location of the nidus in relationship to the skull. It was possible to clearly delineate the course, size, and number of feeding vessels and draining veins. The model made identification of the normal and abnormal vessels easier and assisted in the preparation and conduct of surgery. The model was made to scale and was placed beside the surgeon during the operation. The limitation of current technology was that the exact differentiation of arteries and veins by color coding was not possible. **Conclusion:** 3D printed models can be helpful in getting information regarding the architecture and character of the arteriovenous malformation. The models are cost-effective and easy to build.

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Full Text

Surgical resection forms the only proven and effective treatment modality of arteriovenous malformations (AVMs). However, the conduct of surgery necessarily requires extensive planning as well as meticulous and flawless execution, as any incomplete operation or neurological complication may have a negative impact on the operation. The authors evaluate the usefulness of the emerging technology of three-dimensional (3D) model reconstruction as a preoperative radiological adjunct. The utilization of such 3D models is now becoming a frequently used investigative tool for several brain and spine-related surgical issues.

Technique

Six patients with anatomically complex AVMs or AVMs in eloquent regions of the brain were subjected to computed tomography (CT) angiography with 3D model reconstruction. A digital subtraction angiography was additionally performed in all patients. The information obtained from the catheter angiography and the 3D printed model was analyzed, correlated, and compared.

Technique of printing

Data acquisition

The CT scan data was acquired using a 64-slice scanner (Somatom 64, Siemens, Erlangen, Germany). The scan was obtained from the vertex to a plane 1 cm below the lower margin of the mandible and the occipital condyle after injecting 60 ml iodinated contrast and 20 ml saline chaser at 4.5 ml/s. An arterial phase study was obtained and the images were reconstructed as 0.6 mm slices at 0.5 mm intervals.

Three-dimensional file creation

A 3D volume was created from the axial images using a specialized workstation (Vizua, France). The AVM and the supporting skull [Figure 1], [Figure 2], [Figure 3] were the only structures kept whereas the rest were edited. The resultant volume was transferred to a.zpr file.{Figure 1}{Figure 2}{Figure 3}

Three-dimensional model creation

The.zpr file was transferred to the workstation of a color jet 3D printer (Projet 660, 3D Systems, USA). The average print time was 2–3 hours. After additional 2 hours of cooling, the part was removed and fixed.

Clinical Relevance

Six patients with complex AVMs were treated during August 2015 to December 2016. The patients' age ranged from 11 to 35 years and the mean age was 26 years. The location of the AVM was in the Sylvian fissure in 1 patient, posterior frontal region in 2 patients, subfrontal region in 1 patient, and parietal region in 2 patients. Three patients with an AVM presented with acute symptoms due to an intracranial rupture of the malformation. The patients with acute rupture were managed conservatively at the time of initial presentation and then operated after a period varying from 2 to 3 months. The patient with the Sylvian fissure AVM initially presented with right hemiplegia and slurred speech. He then gradually improved and had mild right hemiparesis of grade 4/5 with minimal Broca's aphasia at the time of surgery [Figure 1]. The other 2 patients recovered from the episode and had no neurological deficits. Three patients with AVMs presented with severe headache and episodes of convulsions. The clinical and radiological features of the patients are elaborated in [Table 1]. The size of the nidus was 3.2–10 cm in size in maximum diameter. In general, the indications of surgery varied widely. Apart from patient-related factors, the angiographic architecture of the AVM and feasibility of surgical resection formed an important indication for surgery. The AVMs were graded into five types based on the experience of the senior author [Table 2]. None of the patients underwent a preoperative embolization.{Table 1}{Table 2}

The 3D model aided in evaluating the anatomy of the AVM. The location of the AVM could be precisely identified on the skull as it was contoured based upon the dimensions of the skull of the individual patient. The 3D model helped in planning the size and site of the craniotomy. The presence of the model obviated the need for neuronavigation. The model provided a useful tool to evaluate the anatomy of the region in a three-dimensional perspective and to prepare for the surgical procedure in all patients. The model could be handled and moved in various surgical positions, and the entire surgical plan could be rehearsed prior to the actual surgery. The number and site of the arterial feeders were identified based on the models. The model helped to distinguish and safeguard the normal vessels, and served as a guide to plan the execution of the surgical steps. The venous drainage was clearly identified on the model. Out of the 6 patients with arteriovenous malformations, 5 were treated surgically. One patient has a large complex AVM. He is currently under observation.

During the surgery, the model was placed close to the operative area and was kept in a position similar to the surgical position. Based on the patient's bony anatomy seen on the model and the location of the lesion, an appropriate location and size of the craniotomy was marked. The dissection of the AVM was done deploying the defined surgical steps of surgery. The feeding vessels were first identified and dealt with. The nidus was then circumferentially dissected from the adjoining brain parenchyma. Information garnered from the digital subtraction angiography and from the 3D model were both used to successfully resect the AVM.

The AVM was successfully resected in all patients. None of the patients developed any new neurological deficit and are all functionally active at an average follow-up of 14 months. The patient with hemiparesis and Broca's aphasia improved progressively, and at a follow-up of 16 months, had near normal speech with minimal right-sided hemiparesis.

Advantages and Limitations

3D printing technology has paved its way into the medical field and is currently being used for both diagnostic and therapeutic purposes. We earlier reported our experience with 3D models for craniovertebral junction anomalies.[1] We have now studied the usefulness of these models for planning surgery for intracranial vascular malformations.

Digital subtraction angiography and reconstructed CT angiography form the mainstay of the diagnosis and treatment of arteriovenous malformations and aneurysms.[2],[3],[4],[5] Although these investigations can provide 3D reconstructed images and are substantially informative, the data obtained is in a two-dimensional format and leaves a lot to imagination. There is a lot of vessel overlap in both these images and it is difficult to grasp the anatomy fully in a 3D perspective. These lacunae can be overcome by a model that is patient-specific by means of 3D printing. 3D printing is a manufacturing process where a graspable object is made by depositing layers of a material and merging them to create a 3D structure.[1] The 3D object can also be color coded imparting an individual color to a specific structure, making identification easier. This can be of greatly significant use in AVMs where the arteries and veins leading to the AVM nidus may be colour coded.

All the patients studied with the help of the model had intricate vascular anomalies. The 3D model proved to be useful in all patients. We could correctly identify the location and number of feeding vessels and the vessels were coagulated at the same point as was preplanned based on the model. The craniotomy was also adequate in size and its precise location was based on the information obtained from the 3D model. Image guidance was not used in any of the patients. The model also showed the exact location of flow-related aneurysms in patients with AVMs [Figure 2]. As the exact shape of the nidus was right in front of the surgeon's eye during the procedure, brain injury could be minimized while dissecting the nidus. A complete excision of the AVM was performed in all patients. This was confirmed intraoperatively by comparing the shape of the excised nidus with the 3D model. Identification and focus on the larger blood vessels reduced the surgical time. Overall, the model made the surgeon comfortable during surgery and the surgical procedure safer.

In all our patients, a routine catheter angiography was also performed. Both the investigations proved to be complementary to each other in the management of the vascular malformations. While the angiography gave information about the flow in the AVM, the 3D model gave an exact understanding of the anatomy.

There have been a few previous reports on 3D models for AVMs.[2],[3],[6] In all these cases, a 3D model of the AVM was made either from 3D rotational angiogram or from MR angiograms. Weinstock et al., used MR angiography to create 3D models.[3] Multiple models were made of the vascular malformation alone and of the malformation along with the surrounding brain. Thawani et al., used catheter angiography to build a model of an arteriovenous malformation based on flow.[2] The arterial and venous components were separated and studied in the form of 3D models. A reconstructed CT angiogram has not been used for 3D model printing. The advantage of using a CT angiogram is that the nidus is visualized with the bony anatomy of the patient's skull. This obviates the need for image guidance in planning the craniotomy. As the model is contoured on the basis of the patient's actually existing anatomy, the craniotomy can be planned with precision depending upon the location of the AVM. Second, along with the abnormal vessels, the relevant normal vessels and their location with respect to the AVM are clearly visualized. The model was placed in the exact surgical position as that of the patient during the actual operation and served as a guide for the vascular anatomy during the surgery.

A limitation of the model is that the blood flow could not be depicted. The arteries and veins were identified on the model based on the location and not on the flow through the vasculature. In future, we envisage that a 3D model can be made by fusing the images of the catheter angiography with the CT angiography and then color coding it. This will give a more accurate representation of the vascular malformation.

3D models are easy to make and are relatively inexpensive. The printing can be accomplished within a few hours and made available promptly. It serves as a teaching tool for neurosurgical residents. Patients can comprehend the extent of their own lesion and the risks and benefits of the treatment. For the operating surgeon, it gives a 3D understanding of the anatomy. Handling of the model in various positions gives a good mental and tactile feedback, serving as a good simulation tool prior to the actual surgery.

Conclusion

3D model printing has the potential to become an essential preoperative investigation for surgery on AVMs.

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Conflicts of interest

There are no conflicts of interest.

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