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Clinical commentary

Three-dimensional intracranial middle cerebral artery aneurysm models for aneurysm surgery and training

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ABSTRACT

To develop a realistic model of middle cerebral artery (MCA) aneurysms using three-dimensional (3D) printing for surgical planning, research, and training of neurosurgical residents. This study included eight MCA aneurysm cases. The aneurysm together with the adjacent arteries and skull base were printed based on raw computed tomography angiography (CTA) data using a 3D printer with acrylonitrile-butadiene-styrene as the model material. The aneurysm models were used for surgical planning, and craniotomy and clipping practice by neurosurgical residents. Feedback was obtained using a survey. 3D aneurysm models were created for all seven MCA aneurysm patients. There was good agreement in the model aneurysm diameter, width, and neck and the CTA data, with no significant difference ($p > 0.05$) among the groups. The simulator was useful for choosing the clips to use before surgery. The average response to each of the survey questions was greater than 3.85 (range 3.0–5.0) on a five-point scale. The 3D printed MCA aneurysm models were accurate. Simulation and practice using the 3D models was useful for understanding the aneurysm structure and choosing the clips to use before surgery, especially for junior neurosurgeons.

1. Introduction

Approximately 0.6% to 6% of the population has an intracranial aneurysm and the rupture rate is about 2% per year [1]. These are responsible for 80% of all spontaneous subarachnoid hemorrhages [2]. The mortality risk is approximately 60% at 6 months [3].

Increasingly, aneurysm patients undergo endovascular treatment, reducing the amount of open surgery [4], especially in the developed countries [5]. Consequently, junior neurosurgeons have fewer chances to practice open surgery. Currently, clips are used to treat middle cerebral artery (MCA) aneurysms more often than coiling. MCA aneurysms usually have wide necks, and the main difficulty during clipping is determining the best clip to use. It is dangerous to adjust or change the clips frequently, particularly in complex and wide-neck saccular aneurysms [6]. Consequently, the surgical plan and three-dimensional (3D) structure of the aneurysm are very important. Over the past few decades, improvements in diagnostic imaging techniques, such as computed tomography angiography (CTA), magnetic resonance angiography (MRA), and digital subtraction angiography (DSA) have made it easier to determine the 3D structure of an aneurysm and the associated microvascular anatomy. Nonetheless, the interpretation of the actual image by neurosurgical residents has limitations. We believe that 3D printing models of the aneurysm can counter this issue.

Three-dimensional printing or rapid prototyping technology has been the subject of several reports on cerebral aneurysms [7–9]. However, no paper has focused on MCA aneurysms using models to study the aneurysm characteristics. Therefore, this study examined the feasibility of using 3D MCA aneurysm models for training junior neurosurgeons.

2. Materials and methods

2.1. Patients

In this study, patients with MCA aneurysm seen in our department from September 2013 to March 2016 were enrolled. The

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inclusion criteria were as follows: MCA aneurysm; CTA and DSA obtained preoperatively; 3D model printed preoperatively; and the MCA aneurysm was clipped.

2.2. Image post-processing

We used Mimics software (Materialise) to process the original CTA or MRA data in digital image and communication in medicine (DICOM) format, applying the vascular threshold values for patients with an aneurysm on CTA. A 3D reconstruction technique was used to construct a 3D intracranial aneurysm model. Mimics takes the multi-plane images of the pretreatment intracranial aneurysms, transforms them into STL format, performs accurate 3D calculations, optimizes the model for the surface grid, sets the data-processing parameters obtained using ANSYS, and gives the 3D printer output for the 3D intracranial aneurysm model.

2.3. 3D aneurysm model printing

The 3D whole printed models were created using an Objet Connex 350 3D printer (Stratasys, Eden Prairie, MN, USA), which uses photosensitive polymers with a Polyjet method. The regional 3D models were created using an 3D printer (Jupu 600, Medprin, China), which used acrylonitrile–butadiene–styrene (ABS) with a fused deposition modeling method. The regional 3D aneurysm model was created according to a method previously described by Mashiko [15]. Briefly, the model was printed using commercially available molding silicone, and a hardening agent was painted on the surface of the model after it cured. The inner ABS of the model was immersed and dissolved in xylene.

2.4. Parameter measurement

Preoperatively, the aneurysm length, width, and neck were measured on the CTA, MRA, and DSA images.

2.5. 3D model evaluation

Six junior neurosurgical residents (experience 2–5 years) completed an operating plan and performed a simulated craniotomy and aneurysm clipping using the 3D model. The ANSPACH system (Johnson & Johnson USA) was used for the craniotomy and a PENTERO 900 (Zeiss, Germany) was used for the aneurysm clipping and picture shot. After performing the operation, they provided feedback in a survey consisting of the seven questions shown in Table 3 [10].

2.6. Statistical analysis

Values are presented as the mean ± standard deviation. The statistical analysis was performed using the Statistical Package for the Social Sciences ver. 16.0 (SPSS, Chicago, IL, USA). The mean measurements of the CTA, DSA, and 3D model were compared using one-way analysis of variance (ANOVA) followed by Fisher's least significant difference (LSD) test. A two-tailed P-value < 0.05 was considered statistically significant.

3. Results

3.1. Patient outcomes

In this study, eight MCA aneurysm patients [5 males, 3 females; mean patient age 51.88 (range 30–67) years] were enrolled. The aneurysm involved the right MCA in three and the left in five. All of the patients underwent aneurysm clipping surgery under general anesthesia (Table 1).

3.2. 3D aneurysm model and evaluation results

All eight patients underwent DSA and CTA (Fig. 1; Fig. 4), and 3D models of the aneurysm were printed using the CTA DICOM data. Some of the aneurysm models included the skull base and parent artery, or just the aneurysm.

We compared the aneurysm diameter, width, and neck on the model and actual CTA and DSA images using one-way ANOVA followed by Fisher's LSD test and found no significant differences ($p > 0.05$) among the groups (Table 2) and the process time and cost of the two kinds of MCA aneurysm models were showed in Table.4.

The clips chosen in the aneurysm clipping simulation were similar to the clips used in the actual surgery, except when the aneurysm had a wide neck and hard wall, when two extra clips were used. We used Yasargil aneurysm clips for the simulation, while the surgeon used Sugita clips in four cases, primarily due to personal preference. The data are shown in Table 1.

In this study, six neurosurgical residents were recruited, with an average of 3.5 (range 2–5) years of training. They completed a survey after practicing a craniotomy and aneurysm clipping using the 3D simulator (Figs. 2, 3 and 5). The average response to the survey questions was 3.85 or greater (range 3.85–4.75) on a five-point scale. Table 3 shows the questions and the mean responses and ranges. The scores were high for two of the questions about the simulator. These asked whether it improved the resident's understanding of the relationship of the aneurysm to the parent artery and whether the simulator was useful for training.

4. Discussion

Currently, the use of 3D printing in medicine is being explored, and 3D printing of plates, artificial joints, and prostheses has been used clinically [11]. Customized cranioplasty implants using 3D

Table 1
Summary of the patients.

Patient	Age (years)	Sex	Lesion	SAH	Clips used on the model	Clips used in the actual surgery
1	67	F	R MCA	yes	FT650T, FT640T	FT650T, FT640T
2	45	M	L MCA	yes	2 FT819T	2 Sugita 1,700,120
3	50	F	L MCA	no	FT720T	FT720T
4	64	M	R MCA	no	FT762T, FT720T	2 Sugita 1,700,215, FT722T, FT762T
5	43	M	L MCA	no	FT720T	FT720T, FT710
6	65	F	R MCA	no	FT752T	FT752T
7	30	M	L M2	no	FT760T	Sugita 1,700,110
8	51	M	L MCA	no	FT780 FT623 Yasargil long clip	2FT780 FT623 Sugita 1,700,190

F, female; M, male; R, right; L, left; MCA, middle cerebral artery; SAH, subarachnoid hemorrhage.
Sugita 1,700,120 equals FT819T, Sugita 1,700,215 equals FT726T, Sugita 1,700,110 equals FT760.

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