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3D printing of intracranial aneurysm based on intracranial digital subtraction angiography and its clinical application

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Abstract

The study aimed to develop simulation models including intracranial aneurysmal and parent vessel geometries, as well as vascular branches, through 3D printing technology. The simulation models focused on the benefits of aneurysmal treatments and clinical education. This prospective study included 13 consecutive patients who suffered from intracranial aneurysms confirmed by digital subtraction angiography (DSA) in the Neurosurgery Department of Shaoxing People's Hospital. The original 3D-DSA image data were extracted through the picture archiving and communication system and imported into Mimics. After reconstructing and transforming to Binary STL format, the simulation models of the hollow vascular tree were printed using 3D devices. The intracranial aneurysm 3D printing simulation model was developed based on DSA to assist neurosurgeons in aneurysmal treatments and residency training. Seven neurosurgical residents and 15 standardization training residents received their simulation model training and gave high assessments for the educational course with the follow-up qualitative questionnaire. 3D printed simulation models based on DSA can perfectly reveal target aneurysms and help neurosurgeons select therapeutic strategies precisely. As an educational tool, the 3D aneurysm vascular simulation model is useful for training residents.

Abbreviations: 3D = three-dimensional, aSAH = aneurysmal subarachnoid hemorrhage, CTA = computed tomography angiography, DSA = digital subtraction angiography, GDC = Guglielmi detachable coil, IARAT = Intracranial Aneurysm Rerupture After Treatment, IPR = intraprocedural rerupture, mRS = modified Rankin scale, WFNS = World Federation of Neurological Surgeons.

Keywords: 3D printing, aneurysms, digital subtraction angiography, surgical simulation models

1. Introduction

Intracranial aneurysm is a cerebrovascular disorder in which weakness in the wall of an intracranial artery causes a localized dilation or ballooning of the blood vessel. Both high and low wall shear stress can cause aneurysm and rupture. If an aneurysm ruptures, blood leaks into the space around the brain and causes subarachnoid hemorrhage.

With the development on imaging and microscopic technology, the field of neurosurgery has made great progress, especially on the diagnosis and treatment of aneurysm. At present, it is possible to reconstruct the fine stereo structure of intracranial

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tissues and organs through computed tomography angiography (CTA), magnetic resonance angiography, and digital subtraction angiography (DSA).[1,2] However, a great difference remains between information obtained from medical imaging and the actual stereo tissues or organs in the human body.

Clinical experience during resident standardization training is traditionally obtained from cadaveric training and the observation of different operations. However, the cost and resource of cadavers for surgical training is increasingly prohibitive. Furthermore, most hospitals and standardized training centers offer few opportunities on the observation of different kinds of operations, especially on neurovascular training. One solution to improve the learning of intracranial anatomy and neurovascular disease is to use medical simulators for procedural training. Through simulation, residents can integrate their theoretical knowledge with the physical process and surgical techniques.

Three-dimensional (3D) printing technology can provide simulations based on the medical imaging data, and these personalized models can also help in deciding on surgical strategies and surgical planning. 3D printing is a promising technique that may be applied in medicine. The benefits of simulation are particularly valuable in intracranial aneurysms for neurosurgical resident training. This would allow the surgeon to visually perceive the location and size of the lesion, as well as the direction of the aneurysm. Furthermore, this would also enable them to carefully analyze the relationship between aneurysm and its parent artery. Intracranial aneurysms are found in approximately 2% of adults,[3] and the intraprocedural rerupture (IPR) of aneurysm can lead to disastrous consequences. Intracranial Aneurysm Rerupture After Treatment (IARAT) study evaluated the rates of IPR for surgical clipping (19%) and endovascular

coiling (5%). Furthermore, it was also found that the risk of IPR-associated periprocedural death/disability was 31% with surgical treatment and 63% with endovascular in 2008.[4] In addition, the mortality of intracranial aneurysm decreased to <14% with neurosurgical treatment[5] and <1% with endovascular treatment[6] in 2016. Strengthening the standardized training for residents can effectively reduce medical disputes, self-protect medical staff, and improve medical-patient communication.

3D printing technology is becoming more and more active in the field of medicine. Some scientific research institutions have been successful in the application of 3D printing technology in the field of medical simulation such as artificial blood vessels and biomaterial tissues.[7,8] However, this technology is seldom used in neurosurgery.

2. Materials and methods

This study was conducted in accordance with the declaration of Helsinki. This study was conducted with approval from the Ethics Committee of Shaoxing People's Hospital, Shaoxing Hospital of Zhejiang University. Written informed consent was obtained from all participants.

2.1. General information

This prospective study involved 13 consecutive patients with intracranial aneurysms, who were admitted from April 1, 2016 to July 31, 2016 at the Neurosurgery Department of Shaoxing People's Hospital Zhejiang Province, China. All patients included into this study underwent 3D-DSA. Patients diagnosed with brain death or coma induced by drug overdose, alcohol, or intracranial hernia were excluded from this study. The patients who suspicious of aneurysmal intraluminal thrombus before DSA were also excluded. Among these patients, 12 patients suffered from aneurysmal subarachnoid hemorrhage (aSAH) on admission, and one patient was incidentally detected by CTA due to dizziness. Furthermore, all patients received appropriate stabilization and treatment upon admission to the Neurosurgery Department, and neurologic evaluation was immediately performed. Patients underwent cranial CT scans as soon as possible. Recorded data involved age, gender, aneurysm location, lumen size of the aneurysm, diameter of the neck, World Federation of Neurological Surgeons (WFNS) grade,[9] modified Fisher grade,[10] treatment including clipping and coiling and mRS scores.

2.2. Methods

Imagining capture: intracranial DSA (Philips Allura Xper FD20, the Netherlands, Amsterdam, Netherlands) was routinely performed after appropriate observation and treatment. For the purpose of establishing the vascular model, a 300 mg I/mL injection of iopamidol (Bracco Sine, Shanghai, China) was chosen as the contrast agent. The amount of iopamidol injected was approximately 16 to 17 mL. Injection speed was set at 3 mL/s during internal carotid artery angiography. When vertebral artery rotation angiography performed, injection amount of iopamidol was decreased to approximately 8 to 10 mL, and injection speed was lowered to 2 mL/s. The procedure was performed by neurosurgeon.

Mimics reconstruction: The vascular computational model was reconstructed from the original rotation data to 3D-DSA. Meanwhile, the original imaging data were extracted through the Picture Archiving and Communication System (PACS; eRAD,

China). DICOM was the output data format set for the computer workstations. Multidimensional data sets were imported into Mimics (Materialise 18, Leuven, Belgium), a medical reconstruction software suite. Mimics enabled the reconstruction of the intracranial artery after format conversion and extraction threshold. Then, masks were set up and segmentation was performed to isolate aneurysmal and parent vessel geometries as binary masks. Then, the data were exported to the 3D printer in binary STL format. The procedure was performed by a neurosurgeon and a software engineer in our print team together.

3D printing: The computational vascular model shelled the vessel wall with a thickness of 0.45 mm, which is commercially available to 3D printing technology. The hollow vascular tree was 3D printed using a Connex Multi-Material 3D Printer (MoonRay, Zhejiang, China). The printer model resolution is 0.02 mm. We use photosensitive resin as our material. The thinnest thickness of the vessel wall could reach 0.30 mm. For educational purposes and economic reasons, we printed both the original simulation models (10 dollars) and enlarged models (12 dollars) that involved the target aneurysmal and parent vessel geometries, as well as vascular branches. Neurosurgeons can put the 3D print simulation model on their hands and rotate the aneurysm and parent vessel to see the backside more clearly. They can feel the size, shape, direction, and the relationship with parent artery of the aneurysm visually. And can help neurosurgeons on subsequent treatment of neurosurgical clipping and endovascular coiling. The print and transport procedure were performed by the team from Zhejiang xun-shi Technology Company Limited.

Prognosis evaluation: The modified Rankin scale (mRS) at 2 months after treatment was recorded as clinical outcomes. The mRS scores were as follows: 0 as no symptoms, 1 as minor symptoms, 2 as some restriction, 3 as significant restriction, 4 as partly dependent, 5 as fully dependent, and 6 as dead. In using dichotomous variables, favorable and unfavorable outcomes were defined by mRS scores of 0-2 and 3-6, respectively.

Qualitative validation: To qualitatively validate the simulation model, 7 neurosurgical residents and 15 standardization training residents with other specializations received their simulation model training under the guidance of the Chief Physician of Neurosurgery. In general, the training included 2 major parts. One part is that the chief physician of neurosurgery gave lessons together to the 22 residents in our classroom about the anatomy and pathogenesis of aneurysm, as well as its diagnosis and treatment. Another part is that the 22 residents were divided into groups; each member of the group can put the 3D print simulation model on his hand and rotate the aneurysm and parent vessel to see the backside more clearly. They can feel the size, shape, orientation, and the relationship with parent artery of the aneurysm. Their feedback evaluations were obtained through a specially designed questionnaire. And then we got the scale of evaluation for all correspondence questions.

3. Results

Clinical data recorded from the 13 patients with aneurysm included age, gender, aneurysmal location, lumen size of the aneurysm, diameter of the aneurysm neck, neurosurgical evaluation, WFNS grade, modified Fisher grade, treatments, and mRS. The sample population comprised of 5 males and 8 females, and the mean age of this population was 58.15 ± 10.24 years. The lumen size of the aneurysm was shown as: length: maximum length of aneurysmal dome; width: the length of the aneurysmal dome rotated 180° in the same plane of the previous

Table 1

Clinical data of patients with cerebral aneurysms for simulation model.

Patient	Age	Gender	Location	Size (mm) L × W × H	Diameter of neck (mm)	WFNS	Fisher	Clipping or coiling	mRS
1[*]	49	F	R,MCA	2.20 × 2.10 × 2.60	1.88	IV	IV	Clipping	1
				3.37 × 3.73 × 3.54	2.87				
2	74	F	R,MCA	12.3 × 9.65 × 9.28	6.16	I	I	Coiling	0
3	47	M	L,MCA	1.86 × 1.53 × 1.27	1.35	II	IV	Clipping	1
4	50	F	R,ICA	13.8 × 12.7 × 13.8	3.89	I	I	Coiling	0
5	55	F	L,ICA	6.14 × 5.56 × 5.10	3.49	II	III	Coiling	1
6	46	M	ACoA	3.87 × 3.96 × 5.21	2.59	I	III	Coiling	0
7	59	M	ACoA	3.01 × 4.41 × 2.79	2.02	I	III	Coiling	0
8	48	F	R, PCoA	3.97 × 3.39 × 3.73	2.01	I	III	Coiling	0
9	77	F	L,PCoA	3.69 × 8.25 × 3.85	4.29	V	IV	Clipping	2
10	65	M	ACoA	8.92 × 5.05 × 4.86	2.88	I	III	Coiling	0
11	63	F	R, PCoA	8.03 × 6.74 × 10.5	8.84	I	I	Clipping	0
12[†]	58	M	L,VA	8.64 × 5.05 × 4.86	null	IV	IV	Coiling	2
13	65	F	ACoA	2.67 × 2.26 × 2.89	1.66	III	I	Coiling	1

ACoA = Anterior communicating artery, ICA = internal carotid artery, MCA = middle cerebral artery, mRS = modified Rankin scale, PCoA = posterior communicating artery, VA = vertebral artery, WFNS = World Federation of Neurological Surgeons.

[*] Multiple aneurysms in bifurcation of middle cerebral artery.

[†] Vertebral dissecting aneurysm.

length; and height: the length from the top to the bottom. The mean maximum length was 5.89 ± 3.85 mm. The mean diameters of the neck were 3.38 ± 2.10 mm. The locations, WFNS grades (from I to IV), Fisher grades (from I to IV), treatments (4 patients for clipping, and 9 patients for coiling), and mRS (from 0 to 6) are summarized in the Table 1. The patient incidentally detected by CTA due to dizziness got a good recovery of mRS 0. Whose dizziness was diagnosed as Benign Positional Vertigo and improved after repositioning maneuver therapy. We follow the treatment strategy of AHA/ASA Guideline (2012) including control high blood pressure with antihypertensive medication, reduce the incidence of aneurysm rebleeding, complete obliteration of the aneurysm, determination of aneurysm treatment, as judged by both experienced cerebrovascular surgeons and endovascular specialists, should be a multidisciplinary, and then management of intracranial vasospasm and delayed intracranial ischemia.

The authors successfully 3D printed a simulation model that comprised of a hollow vascular tree of aneurysm and parent artery and its branches with photosensitive resin materials, which exactly matched with the images reconstructed through DSA and Mimics, respectively (Figs. 1–4). For the sake of the neurosurgical applications, the original size of the simulation model and magnify size of the simulation model (scale, 3:1) were both printed.

Seven neurosurgical residents and 15 standardization training residents, who had an average postgraduate year of 3.4 years (range: 1–6 years) received the simulation model training within the next 2 months. The evaluation for all correspondence questions was >4 (range: 4–5 points) on the 5-point scale (Table 2).

4. Discussion

This study attempted to print the 3D simulation models and then help neurosurgeons on make preoperative decisions through its real overall vision, thus minimized the risk of the treatment. These entity photosensitive resin models that had been printed for the purpose of operation also can be used as educational tools in residents training. The main findings of this study are as follows.

Figure 1. The aneurysm reconstructed through 3-dimensional digital subtraction angiography .
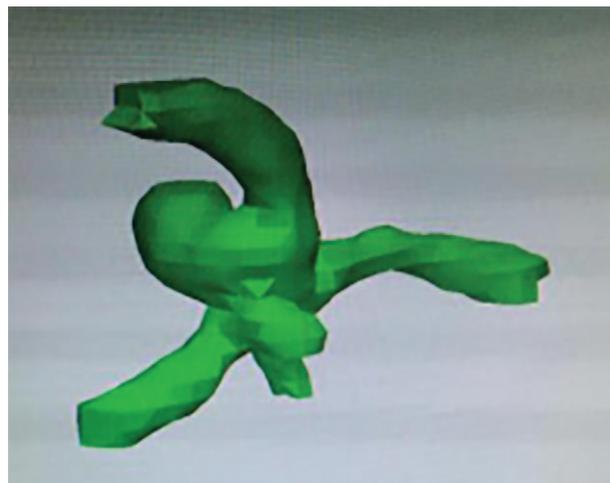
Figure 2. The aneurysm reconstructed through Mimics.

Figure 3. Original size simulation model (left) and magnify size simulation model (scale 1:3 right).

Figure 4. 3D printed aneurysm providing overall vision including the structure hiding behind the linear view of microscope.
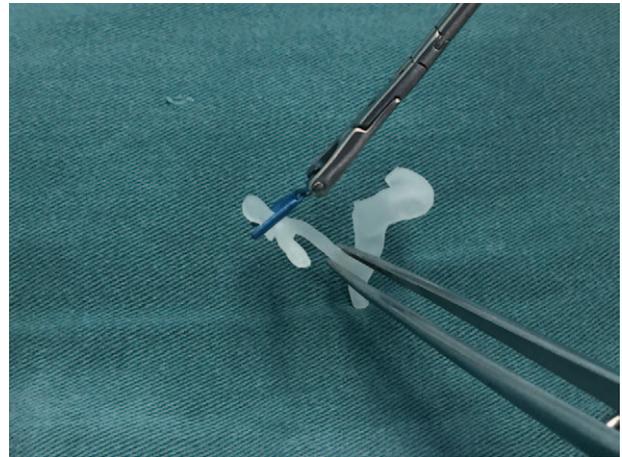
Figure 5. Application of 3D printed simulation model when craniotomy clipping.

Firstly, 3D printed simulation models based on patient-derived DSA can perfectly involve target aneurysmal and parent vessel geometries, as well as vascular branches. With the dawn of 3D printing technology, Sutradhar et al[11] succeeded in reconstructing and 3D printing patient-specific implants using digital image correlations and finite element analyses. Kim et al[12] was able to create a hydrogel template for the functional brain microvascular structure using microneedles and a 3D printed frame. Furthermore, there were also some studies on 3D bioprinting toward tissue and organ fabrication.[13,14] In these simulation models, the target aneurysm and its parent vascular were reconstructed from 3D-DSA, its format was transformed using Mimics, and it was exported to the 3D printer.

Secondly, with the development of the 3D printed simulation models displayed the realistic shape of the aneurysm, great changes have happened at the traditional aneurysm treatment not only on the fields of neurosurgical clipping but also on the endovascular coiling. The treatment strategy of choosing the clipping or coiling exactly determined by the DSA itself, especially by 3D-DSA, not waiting for the 3D printed simulation models. When we decide to perform a surgery procedure based on the DSA data, we can select more appropriate type of clips for the certain patient with the help of 3D printed aneurysm simulation models. It can help neurosurgeons to choose more suitable clips of special shape, size, curvature, and type in vitro during

Table 2

The feedback evaluation questionnaire of the simulation model from residents.

No.	Question	Score mean (range)
1	Is the simulation model clinically applicable?	4.4 (4–5)
2	Did the simulation model help you to comprehend the shape of the aneurysm?	4.8 (4–5)
3	Did the simulation model help you to comprehend the location of the aneurysm?	4.8 (4–5)
4	Did the simulation model help you to comprehend the direction of the aneurysm?	4.8 (4–5)
5	Did the simulation model help you to comprehend the parent artery of the aneurysm?	4.7 (4–5)
6	Did the simulation model improve your understanding on the aneurysmal therapeutic strategy of craniotomy clipping or endovascular coiling?	4.4 (4–5)
7	Did the simulation model improve your understanding on the wide-necked aneurysm and its therapeutic strategy?	4.3 (4–5)
8	Did the simulation model improve your surgical skill?	4.1 (4–5)
9	Did the simulation model improve your medical-patient communication skill?	4.6 (4–5)
10	Was the simulation model training course useful to you?	4.8 (4–5)

Figure 6. Application of 3D printed simulation model when endovascular coiling.

operation but without touching the aneurysm itself (see Fig. 5). When we decide to perform an endovascular coiling, we can choose more suitable size of the Guglielmi detachable coils (GDCs) to frame aneurysms initial progressively sized loops as well as Microcatheters and microfilaments according to the 3D printed simulation (see Fig. 6). Of course, with the help of 3D printed simulation models, we can verify the accuracy of selecting therapeutic strategy based on DSA in reverse. Aneurysmal subarachnoid hemorrhage remains one of the most challenging diseases, and its surgical intervention is difficult due to complicated anatomy craniotomy. Furthermore, it remains controversial whether clipping or endovascular coiling treatment should be recommended.[15–17] Some studies suggest that surgical strategy depends on the size, location, and direction of the aneurysm itself, as well as the WFNS or Fisher grade of the patient.[18] Ripley et al[19] found that the 3D model based on cardiac assists anatomic visualization may complement traditional techniques. Namba et al[20] had applied 3D printing technology to improve aneurysm coiling. In our study, the original size simulation model and magnify size simulation model (scale 3:1) were both printed to meet neurosurgical application requirements. The magnify models help neurosurgeons in neurosurgical clipping and endovascular coiling to some extent. The original models provide the real aneurysmal shape and its adjacent structures, especially the important anatomic visual structure hiding behind the linear view of microscope as reference during operation.

Thirdly, the primary use of this technique is in preoperative planning, and we also find we can use these 3D simulation models in training. Educational tools based on the 3D aneurysm vascular

simulation model have effectively demonstrated its usefulness in training neurosurgical residents and standardization training residents. Ryan et al built a simulacrum for simulating aneurysm clipping, which comprised of 3 distinct components; and they found that these simulation models were promising and useful as educational tools.[21] A total of 22 residents received the simulation model training in the study. The evaluation for all correspondence questions was >4 (range: 4–5 points) on the 5-point scale. They felt that the simulation models were clinically applicable, and that these models helped them comprehend the shape, location, and direction of the aneurysm. With 3D anatomic visualization, the simulation models help them to understand the parent artery of the aneurysm and improve their medical-patient communication skill. So, comparing to the 3D-DSA, the benefit offered from this technique is that 3D printed models are real; neurosurgeons could see more concrete details about the aneurysm while putting them on their hands. And doctors could look down from the top or other directions while rotating them on hands completely at ease. The pictures of reconstruction 3D-DSA on the screens are difficult to some residents and students.

Our study still had some limitations. The model integrated only vascular branches of the target aneurysm. Other important anatomical relationships such as other optic chiasm, cranial nerves, skulls, and brains were not included. The demand for cerebrovascular surgery requires more comprehensive simulation models suitable for the education of medical professionals. Furthermore, the efficiency of this educational course should be evaluated to support larger training studies with different operational skill levels. For the next step, we will attempt to evaluate the correlation surgical intraoperative findings and the printed images. And we will attempt to use the 3D printing rapid prototyping technology on microcatheter shaping for intracranial aneurysm coiling also.

5. Conclusion

3D printed simulation models based on DSA can perfectly reveal the target aneurysm and help neurosurgeons select the appropriate therapeutic strategy. As an educational tool, the 3D aneurysm vascular simulation model has demonstrated its usefulness for training neurosurgical and standardization training residents.

Author contributions

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Writing – review & editing: Zi-Gang Yuan, Guo-Liang Qian, Wu-Qiao Bao, Guo-Liang Jin.

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