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Three-dimensional brain arteriovenous malformation models for clinical use and resident training

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Abstract

Background: To fabricate three-dimensional (3D) models of brain arteriovenous malformation (bAVM) and report our experience with customized 3D printed models of patients with bAVM as an educational and clinical tool for patients, doctors, and surgical residents.

Methods: Using computerized tomography angiography (CTA) or digital subtraction angiography (DSA) images, the rapid prototyping process was completed with specialized software and "in-house" 3D printing service. Intraoperative validation of model fidelity was performed by comparing to DSA images of the same patient during the endovascular treatment process. 3D bAVM models were used for preoperative patient education and consultation, surgical planning, and resident training.

Results: 3D printed bAVM models were successful made. By neurosurgeons' evaluation, the printed models precisely replicated the actual bAVM structure of the same patients ($n=7$, 97% concordance, range 95%–99% with average of <2 mm variation). The use of 3D models was associated shorter time for preoperative patient education and consultation, higher acceptable of the procedure for patients and relatives, shorter time between obtaining intraoperative DSA data and the start of endovascular treatment. Thirty surgical residents from residency programs tested the bAVM models and provided feedback on their resemblance to real bAVM structures and the usefulness of printed solid model as an educational tool.

Conclusions: Patient-specific 3D printed models of bAVM can be constructed with high fidelity. 3D printed bAVM models were proven to be helpful in preoperative patient consultation, surgical planning, and resident training.

Abbreviations: 2D = two-dimensional, 3D = three-dimensional, bAVM = brain arteriovenous malformation, CTA = computerized tomography angiography, DSA = digital subtraction angiography.

Keywords: 3D printing, brain arteriovenous malformation, patient consultation, resident training, surgery planning

Editor: Bernhard Schaller.

Contributors: MQD, JYL, GZC, KQ, and XWD acquired and analyzed the data. MQD performed the statistical analysis and drafted the manuscript. CP, DZ, and XFL interpreted the data and contributed to critical revision of the manuscript for important intellectual content. GZC performed critical supervision of the manuscript. All authors read and approved the final manuscript.

Data sharing statement: All data are included in the study.

Funding statement: This work was supported by Guangzhou Science and Technology Program key projects, China grant number 2014J4100042 and Guangdong Science and Technology Department, China grant number 2013B021B00179.

Ethics approval: The study was approved by the Research Ethics Committee of Guangdong General Hospital.

The authors have no financial and conflicts of interest to disclose.

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Medicine (2018) 97:3(e9516)

Received: 28 June 2017 / Received in final form: 2 November 2017 / Accepted: 8 December 2017

http://dx.doi.org/10.1097/MD.0000000000009516

1. Introduction

In the endovascular treatment of brain arteriovenous malformation (bAVM), a thorough understanding of the anatomical structure, including the feeding arteries, nidus, draining veins, and their spatial relationship of the bAVM complex is of great importance.

In the past, the neurosurgeons had to mentally reconstruct three-dimensional (3D) image of the bAVM complex using two-dimensional (2D) images, which requires extensive training and clinical experience, making it a difficult task for young neurosurgeons.

With the development of diagnostic radiologic imaging technology, it becomes easy to obtain 3D images of bAVM structures at desired angles using 3D computed tomographic angiography (3D-CTA) or 3D digital subtraction angiography (3D-DSA) for presurgical simulation and planning. But all these images can only be presented on computer screen to provide only visual sense. A solid vascular model of a specific patient, produced precisely based on his/her CTA or DSA data, which can be hold in surgeon's hand and viewed from different angles by simply rotating it, would be of great help for people with less or no training, such as residents and patients, to understand the anatomic structure and severity of the bAVM. 3D printing technology is perfect for this and makes it come to realism.

3D printing technology is an additive process based on inkjet printing principles, and is capable of generating objects in 3D, from 2D images. After its introduction in the biomedical field, several applications of fabricating and using of models to ease surgical planning and simulation,[1–4] in implantology,[5] neurosurgery,[6–8] and orthopedics,[9] as well as for the fabrication of maxillofacial prostheses[6,10–14] were reported. The application of 3D printing technology in bAVM has been suggested, but explored less. Because of the complex structural property of bAVM, it is difficult to reconstruct the bAVM models in the computer and the clinical value of bAVM models is still not clear. Thus, the aim of this study is to evaluate the feasibility of fabricating 3D bAVM models, to validate intraoperative model fidelity, and the use of medical models as an adjuvant for surgical planning, patient consultation, and resident training.

2. Methods

2.1. Patient selection

Fourteen consecutive patients undergoing elective endovascular treatment between February 2015 and June 2015 in our institution were included in this study, 7 of them were in the control group without the use of 3D models and the other 7 patients were in the trial group with the use of 3D models.

The research was approved by the Research Ethics Committee of Guangdong General Hospital No. GDREC2014267H (R1).

Written informed consent was obtained from all patients or patient's legal representative prior to inclusion in the study.

2.2. Fabrication of 3D models

Models were constructed based on DSA or CTA data. Regions of interest were identified by neurosurgeon and reviewed with neuroradiologist. The data of bAVM were processed and edited by Mimics software v14.01 (Materialize Corp, Leuven, Belgium). Mimics interactive image processing functions, such as "Threshold," "Region growth," and "Edit," were used to segment the contours of bAVM. After calculation, the 3D images of bAVM and skulls were reconstructed and exported in the form of a standard STereoLithography file format (Fig. 1). Subsequently, these images were imported and printed via 3D printer Stratasys

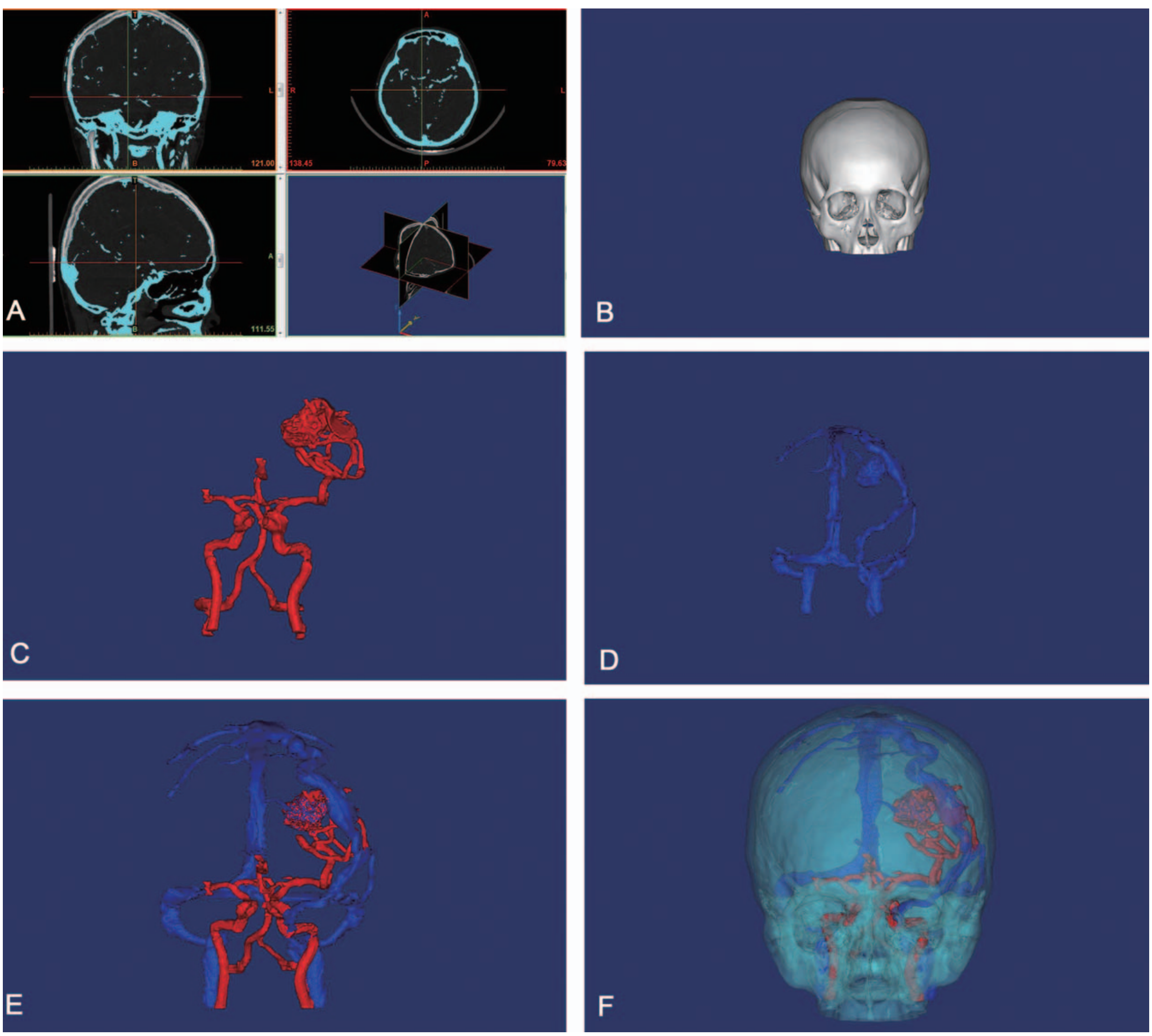

Figure 1. (A) In the three-dimensional (3D) printing of bAVM models, computed tomography data are used to accurately reconstruct the geometry of cerebral vessels and the skull. (B–F) The reconstruction of models includes skull (B), feeding arteries (C), and draining veins (D). (E) It shows the feeding arteries, nidus, and draining veins together. (F) The skull is made transparent to offer a 3D impression of vessel geometry simultaneously to bony structure. 3D = three-dimensional.

J750or Spectrum Z TM 510 (3D systems, Rock Hill, SC) into solid models.

2.3. Questionnaire for patient consultation

We assessed the presurgical patient–doctor communication effectiveness and patients' satisfaction of presurgical consultation with 3D models using a questionnaire. Items on the questionnaire were focused on (1) ease of understanding treatment options for bAVM and surgical risks; (2) benefits and bad influence of solid models for patients. About 10 points for each item and score >7 was defined as satisfied.

2.4. Value of 3D models for neurosurgeons

With life-sized 3D printed models, surgeons intuitively visualized the spatial structures of bAVM and made individualized endovascular treatment plans (Fig. 2). Sizing fidelity was assessed by comparing intraoperative DSA images with models from the same angle of approach.

2.5. 3D models for resident training

We evaluated the use of bAVM models with a group of surgical residents. Thirty surgical residents from residency program—Guangdong General Hospital—responded to a questionnaire. This questionnaire consisted of 20 questions that were scored using a combination of dichotomous-response items (Yes/No), 5-point Likert scales, and open-ended questions. The primary goal of the survey was to assess the usefulness of the bAVM models as an educational tool and determine to what degree it resembled the real bAVM structures.

2.6. Data analysis

Statistical analysis was performed with SPSS 20.0 software (IBM Corporation, Armonk, NY, USA). Independent-Sample T Test was used to evaluate presurgical patient consultation effectiveness, patients' satisfactory degree, and value in surgical planning by using 3D printed models. $P < .05$ was considered to be statistically significant.

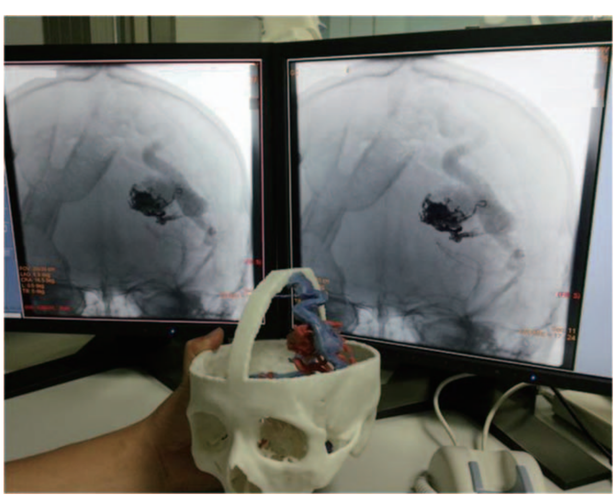

Figure 2. The bAVM model is used for surgical planning to decide which artery to be embolized and what embolization materials to be chosen. This picture shows that the printed bAVM complex is the identical to the one we encounter during surgery. bAVM = brain arteriovenous malformation.

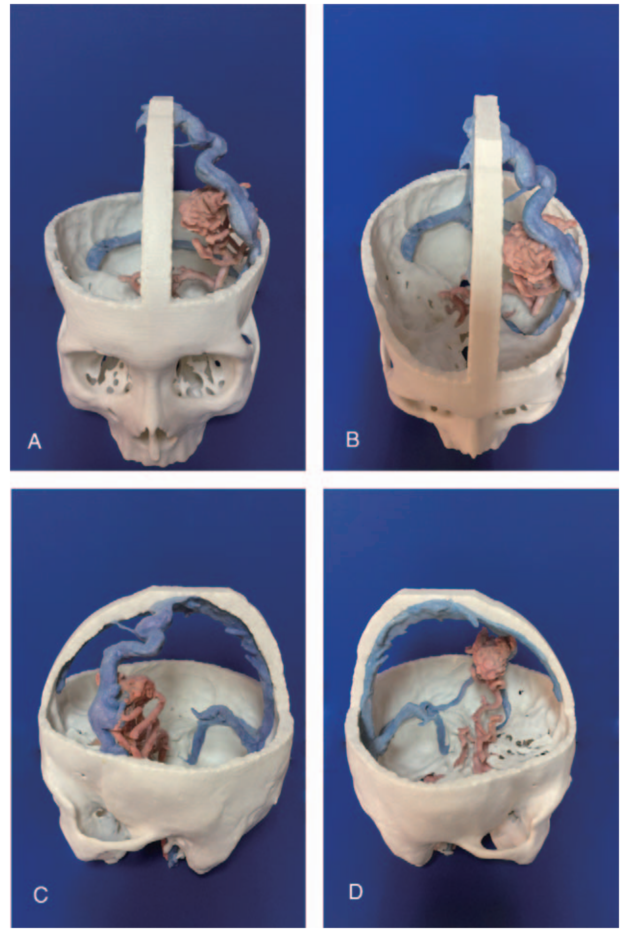

Figure 3. A representative printed model.

3. Results

3.1. Model fidelity

Assessment of 7 bAVM models demonstrated high fidelity between 3D models and actual intraoperative DSA images, with <10% deviation in size. Measurements on the models and intraoperative DSA imaging were each taken in triplicate and compared for deviation. Overall, there was 97% agreement [n = 7, average vessel size: 3.6 mm (model) vs 3.5mm (DSA), range 95%–99% with average of <2 mm variation] in measurements in vessel size. A representative printed model photograph is shown in Figure 3.

3.2. Clinical results

Successful embolization of the bAVM was accomplished without complication. The differences between with and without the use of 3D models are: shorter time for preoperative patient education and consultation, more acceptable for relatives and patients, shorter time from getting intraoperative DSA data to the start of endovascular treatment. A summary of these results is provided in Table 1.

3.3. Residents' responses

Thirty surgery residents participated in the evaluation survey. Detailed responses concerning residents' use of the bAVM

Table 1

The influence of 3D models on informed consent, treatment planning and degree of satisfaction of patients.

	N	Informed consent, minutes	Treatment planning, minutes	Degree of satisfaction
With model	7	10.30±0.80	5.50±0.40	9.40±0.60
Without model	7	15.40±1.30	10.40±1.60	8.20±0.30
T value		8.84	7.86	4.73

3D=three-dimensional, N=number; min: minute.

models are given in Figure 4. On a 5-point Likert scale, about 80% of participants agreed that bAVM model is a useful education tool, whereas 10% disagreed. A total of 66% of participants thought that the bAVM models can increase their understanding of bAVM structures, whereas only 14% disagreed. Only 40% agreed the bAVM models were identical to the one encountered in real surgery. A total of 70% of participants thought that the bAVM models would help define which feeding artery chosen to be embolized, whereas 20% disagreed. In summary, the highest rated feature of bAVM model was its usefulness as a practical educational tool.

4. Discussion

The technology used in fabricating actual 3D human anatomy models from diagnostic imaging data is rapid prototyping.[15] It emerged in the 1980s and progressed in accordance with the advances in computer technology. D'Urso et al[16] are thought to be the first to publish an article on modeling cerebral arteries using rapid prototyping technology with stereolithography. Wurm et al[17,18] and Kimura et al[19] reported model fabrication and preoperative simulation using a similar technique. This study showed the feasibility of manufacturing 3D bAVM models using rapid prototyping technology, from CTA or DSA images, to be used as an adjuvant in surgical planning and informed consent to the patients, as well as being an educational tool for residents.

Being identical to the actual structures, bAVM models can provide stereoscopic viewing, which enhance spatial understanding and facilitate the prediction of surgical techniques and approaches during the preoperative period. As the ordinary planar 3D image is merely a 2D image created with the perspective techniques, it gives no stereoscopic sense in the still state. The perception of the image on the monitor as being 3D is produced by image processing in the viewer's brain based on parallax caused by facts such as image movement, memory, knowledge, and experience.[20] An actual physical model, on the other hand, offers the brain adequate visualization of surrounding structures and clear identification of all involved vessels; thus, a clear understanding of 3D spatial relationship within the neurocranium. We have demonstrated 2 important findings in

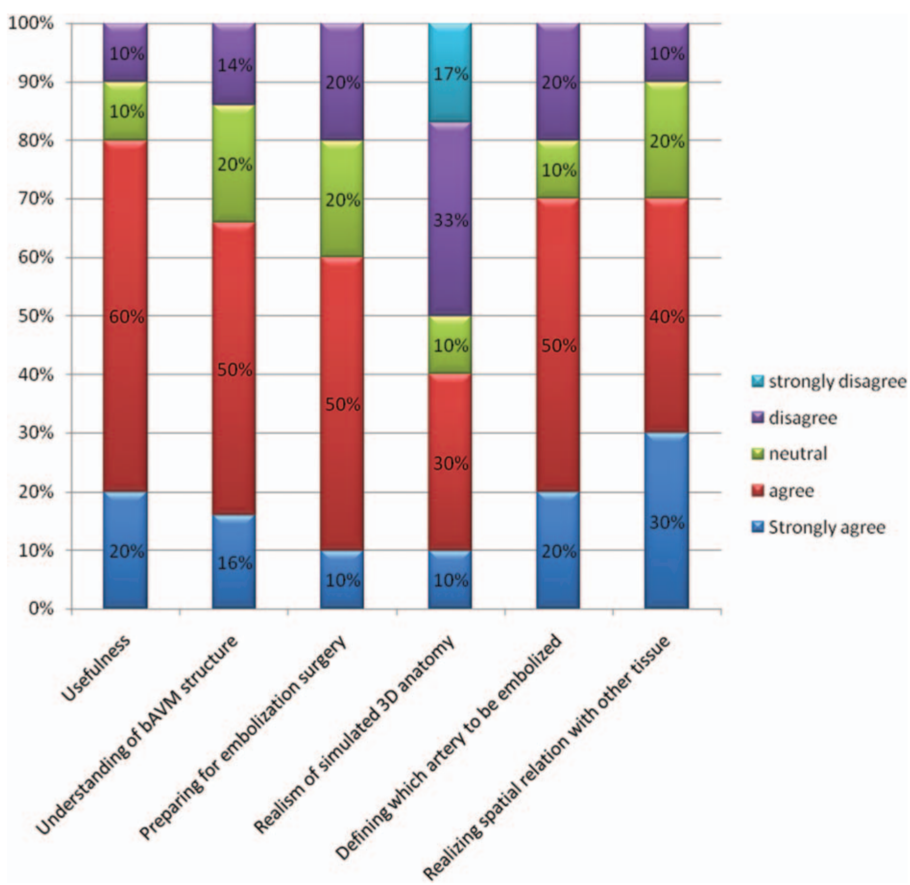

Figure 4. The result of the residents' assessment, which was based on 5-point Likert scales where 5 represents the highest rank and 1 represents the lowest rank.

our study: First, with the aid of 3D printed bAVM models, the actual time needed for patient consultation was considerably shorter. Second, we have shown that neurosurgeons need less time to start intervening treatment after DSA imaging data were obtained during which neurosurgeons determine the optimal intervening treatment plan. In fact, surgeons have gotten thorough, stereoscopic and rotational views of the bAVM structure including feeding arteries, nidus, and draining veins preoperatively using 3D printed models, so the corresponding treatment strategies, such as which artery to be embolized and what embolization material to be chosen have already been made before DSA images were obtained. It is also important to emphasize that an actual solid model of the preoperative 3D surgical anatomy may potentially reduce operative time and surgical risks, which is of great benefit to our patients.

A 3D printed model can also provide real-time intraoperative monitoring in the following aspects: (1) the extent of embolization in endovascular treatment or tumor excision in microsurgery, (2) the location of residue nidus and its relationship with feeding arteries and draining veins, (3) the positional relationship of the lesion and surrounding structures, which improves therapeutic efficacy and decreases surgical complications.

The process of informed consent to the patient about the diagnosis of bAVM and its treatment strategies, with possible risks and benefits, is another significant advantage of this technique. In fact, bAVM models can facilitate the explanation of the case and surgical risk to the patients and their relatives.[18,19] The results of our questionnaire showed that satisfactory degree of patients and their relatives is obviously increased by using bAVM models in preoperative doctor–patient communication. Finally, it is important to emphasize that an actual physical model of the 3D surgical anatomy obtained preoperatively provides great confidence to the surgeons, and consequently benefit for the patients, and may even improve doctor-patient relationship.

Based on the survey results, bAVM models as a teaching method obtained the highest score in all the survey questions concerning their overall usefulness. The participants gave high scores on the ability of bAVM models to build on residents' current understanding of bAVM anatomy. The question whether the bAVM models would help them in preparing for the bAVM endovascular treatment (choosing which artery to embolize) was also rated highly by residents. When asked to what extent the models mimic real anatomy, the scores were moderate (40%) because they thought the structures of the bAVM nidus were not clearly presented by the 3D printed models. This is another research area that needs attention and can be further improved. More realism in graphics is an area of active research, and while we have come a long way, more needs to be done. While it is difficult to assign a statistically proven value to the benefit of this technology, we sought to assess its current usefulness in surgical planning, patient consultation and training of surgical residents as a guide for further development.

5. Conclusion

Further study of 3D printing technology application in neurovascular disease still needs to be carried out. The use of 3D printed models has highest value in aneurysm clipping, preoperative simulation, and accurate understanding of the local anatomy. With printed bAVM models, the surgeon can be aware of the structural property of nidus and related vessels, guiding in treatment planning. However, the models still have some limitations. Fabrication cost and time varied with model size and our models do not yet give information about detailed structures directly inside the nidus. Models that can overcome these limitations are the efforts of our ongoing study on human biomodeling.

Acknowledgments

We thank all the authors for their effort in this study. We also thank Medprin Regenerative Medical Technologies Company Limited for technical support.

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