A new method of intracranial aneurysm modeling for stereolithography apparatus 3D printer: the "Wall-carving technique" using digital imaging and communications in medicine data

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Abstract

Purpose

To assess the ability of the “wall-carving (WC) image technique,” which uses vascular images from three-dimensional digital subtraction angiograms (3DDSAs). Also, to verify the accuracy of the resulting 3D-printed hollow models of intracranial aneurysms.

Methods

The 3DDSA data from nine aneurysms were processed to obtain volumetric models suitable for the stereolithography apparatus. The resulting models were filled with iodinated contrast media. 3D rotational angiography of the models was carried out, and the aneurysm geometry was compared with the original patient data. The accuracy of the 3D-printed hollow models’ sizes and shapes was evaluated using the nonparametric Wilcoxon signed-rank test and the Dice coefficient index.

Results

The aneurysm volumes ranged from 34.1 to 4609.8 mm^3 (maximum diameters 5.1–30.1 mm), and no statistically significant differences were noted between the patient data and the 3D-printed models ($p = 0.4$). Shape analysis of the aneurysms and related arteries indicated a high level of accuracy (Dice coefficient index value, 88.7–97.3%; mean [± standard deviation (SD)], 93.6% ± 2.5%). The vessel wall thickness of the 3D-printed hollow models was 0.4 mm for the parent and 0.2 mm for small branches and aneurysms, almost the same as the patient data.

Conclusion

The WC technique, which involves volume rendering of 3DDSAs, can provide a detailed description of the contrast enhancement of intracranial vessels and aneurysms at arbitrary depths. These models can provide precise anatomic information and be used for simulations of endovascular treatment.

Abbreviations

ICA = internal carotid artery; IC-PC = internal carotid-posterior communicating; A ChoA = anterior choroidal artery; Acom = anterior communicating artery; MCA = middle cerebral artery; BA = basilar artery; Cav = cavernous

Introduction

Three-dimensional (3D) printing technology is developing rapidly. Recently introduced 3D printers can generate human anatomic models in the fields of neuroendovascular surgery. [1] These models can provide an improved understanding of anatomy for preoperative planning and training. [2 3] There are several 3D printing methods, including selective laser melting, laser sintering, fused deposition melting (FDM), stereolithography apparatus (SLA), and laminated object manufacturing. [4 5] FDM is one of the most widely used and least expensive methods; however, it cannot produce hollow models. [6] In contrast, while SLA can create a 3D-printed hollow model, processing the original image data is most important. [7] A method of creating a 3D-printed hollow model of standard triangulated language (STL) data using the hollow-free application has been reported. [8] Small vascular segments with an inner diameter of 1 mm or less have been reported to be prone to apparent blockage of short segments, however, as STL data is difficult to edit in detail. [9] Considering this background, we devised a new hollow model creation technique, the "wall-carving image (WC) technique." This used the digital imaging and communications in medicine (DICOM) data of three-dimensional digital subtraction angiograms (3DDSAs) and a workstation (Ziostation2, Ziosoft Inc., Tokyo, Japan). [10 11] This method can preserve the accurate representation of small vascular segments of 1 mm diameter or less.

In this study, we aimed to verify the accuracy of 3D-printed hollow models of intracranial aneurysms created from DICOM data. We used the WC technique by evaluating the sizes and shapes of the aneurysms and related arteries to enable preoperative simulation of the neuroendovascular treatment.

Material and Methods

Study Design

All procedures involving human participants were in accordance with the ethical standards of our institutional research committee and with the 1964 Helsinki declaration and its later amendments. Written informed consent was obtained from all patients before DSA and treatment. Written informed consent for this study was not required because of the noninvasive study design.

In this single-center, retrospective study, 3D-DSA data from nine aneurysms were manually selected to represent common aneurysm configurations. We included saccular (n = 6) and giant (n = 3) aneurysms with different dimensions and neck configurations (Table 1).

3D-DSA Image Acquisition

All clinical 3D rotational angiography data were acquired using an Artis zee biplane (Siemens Healthcare GmbH, Forchheim, Germany). During the 5 s run, the rotational angle was 200° with a 1.5° increment. There were 133 projections with a matrix of 1024 × 1024 image elements. The active imaging size was 382 mm × 293 mm for 2480 × 1920 pixels. The digitization depth was 16 bit, and the pixel pitch was 154 μm. The following imaging conditions were adopted: 3D acquisition: 70 kV, 12.5 ms, small focal spot, 0.36 μGy/frame, Sub/Nat Mask Recon.: 512 × 512 matrix, 0.22–0.34 mm SL. Hounsfield units, Auto. Workstation: syngo X Workplace (Siemens Healthcare). Iopamidol (Iopamiron, 370 mg I/mL, Bayer HealthCare, Leverkusen, Germany; Oiparomin 370 [370 mg I/mL] or Oiparomin 300 [300 mg I/mL]).

Model Fabrication (DICOM Data Processing)

After patient selection, all image data were anonymized. The 3DDSA data were used to create computer-aided design (CAD) files. Ziostation2 software (Ziosoft Inc.) is used to create CAD files of hollow intracranial vessels and aneurysm models. The 3DDSA data were loaded onto a 3D workstation with Ziostation2 software and were automatically reconstructed into isotropic data. We then generated the WC image. Redundant vascular structures were isolated and stripped to obtain binary images representing the aneurysm and a short adjacent segment of the parent vessel. Small vascular branches such as the anterior choroidal artery were digitally shortened or removed if not immediately relevant to the aneurysm access route to improve the physical stability of the models. The WC technique is a simple volume-rendering (VR) method that uses a subtraction technique on two different 3D data sets of a hollow organ. [10 11] This technique uses the vascular lumen as a "carving tool" to visualize the vessel wall. The main VR technique process for WC is to extract vessel wall volumetric data at an arbitrary depth in the layer parallel to the cerebrospinal fluid cavity–vascular lumen interface (Figure 1). Since the vascular lumen was filled with contrast, a cerebrospinal fluid cavity-filled vascular lumen was easily removed from the source data in a negative gradient display. Next, the non-expanded pure vascular lumen (0 voxels) and the digitally expanded vascular lumen at an arbitrary number of voxels (e.g., 2, 4, or 6 voxels) were selected on the workstation and removed from the respective original 3D datasets to prepare the different range-expanded masks. The volumetric vessel wall data at an arbitrary depth were reconstructed using the image subtraction technique from two different range-expanded masks. The maximal digital expansion was defined as four voxels (0.4 mm) from the cerebrospinal fluid cavity–vascular lumen interface of the intracranial carotid artery based on an estimated thickness of the normal intracranial carotid artery wall of approximately 0.3 to 0.5 mm. [12] The data were converted into an STL file and output to a 3D printer.

The following procedure was used if the aneurysm was in the distal portion or had small branches that needed to be preserved. First, the aneurysm and small vessels were separated from the parent artery. Using the above method, the aneurysm data was expanded by two voxels (0.2 mm), the blood vessel data excluding the aneurysm was expanded by four voxels (0.4 mm), and the original data of each were subtracted. Finally, each set of subtracted data was added (Figure 2).

We fabricated a hollow intracranial aneurysm model from acrylonitrile butadiene styrene with a 25 μm layer thickness using a Form 3 (Formlabs Inc., Somerville, MA, USA). Resin residuals on the surface were cleaned mechanically with 2-propanol using Form Wash (Formlabs Inc.), and the supports were removed from the model.

Model Evaluation

After the 3D-printed hollow models were filled with contrast medium, 3DDSA was performed for each. The protocol was the same as used for the patients, and the analysis was performed using the *syngo* X Workplace. The 3D-printed hollow models' 3DDSA data were processed using the same image analysis workstation to evaluate whole-model shapes, including the aneurysm and related arteries (i.e., the proximal and distal arteries connected to the aneurysm). The edges of the segmented aneurysm and related arteries were manually cut by comparing patient 3DDSA and model data.

The aneurysmal volume was calculated as follows: volume = $4/3\pi \times (a/2) \times (b/2) \times (c/2)$, where a, b, and c denote the height, length, and width of the aneurysm, respectively. This was the same way that volume measurements of aneurysms were determined from the 3DDSA data. [13] Diameters were measured completely blind to cases by a single investigator with 6 years of radiology experience.

After software-based image registration (Matlab, version 9.0.0, MathWorks, Portola Valley, CA, USA) was performed, the whole shape of the segmented aneurysm and related arteries from the patient 3DDSA was compared with the model data using the Dice coefficient index (S). [13, 14] This index, is a measure of the anatomic accuracy of the model. It was calculated as follows: $S = (2 \times OL)/(A + B)$, where A and B are the voxel numbers of the segmented areas of the patient data and model, respectively, and OL denotes the overlapping voxel numbers. This index of similarity yields values from 0 (denoting no overlap) to 1 (denoting identical complete overlap).

Volume differences between patient data and the hollow aneurysmal models were statistically analyzed with JMP10 software (SAS Institute Inc., Cary, NC, USA). The nonparametric Wilcoxon signed-rank test was used, and $p < 0.05$ was taken as a statistically significant difference.

Results

The morphological characteristics of all aneurysms and corresponding vascular models are summarized in Table 1. All models were successfully produced. In the four cases of aneurysms with a small branch, all the small branches were preserved. In one model, the ophthalmic artery with the aneurysm was preserved. A fenestration of the anterior cerebral artery was seen in Model 4 (not shown). Model fabrication typically took from 8 to 12 h, depending on the volume of the photopolymerized material, including the 3D objects and supports. Image segmentation and preparation took approximately 20 min, and the printing process took 7 to 10 h. The removal of resin residuals on the surface and support material required 1 h (depending on the geometric complexity of the model).

Aneurysms with volumes ranging from 34.1 to 4609.8 mm^3 and maximum diameters ranging from 5.1 to 30.1 mm were successfully reproduced (Figs. 1–3). The mean aneurysm volumes for the patient data were not significantly different from the vascular models (1006.1 and 1010.98 mm^3, $p = .4$). The mean Dice index was 93.6% ± 2.5%. No other significant anatomic discrepancies were observed. The vessel wall of the 3D-printed hollow models was 0.4 mm for the parent and 0.2 mm for small branches and aneurysms. There was no contrast leakage of the walls in the models produced for the final analysis. Due to the surface properties, wire and catheter navigation within the models was somewhat impeded by the relatively light friction. Integration of the models into a vascular model with flow was easy, and the models could be accessed with a microcatheter (Figure 4).

Discussion

Anatomic models (also sometimes called phantoms) play a key role in medical training, education, development, and testing new devices. Several methods for the creation of 3D vascular replicas have been described. They are useful because of the increased need to reliably recreate disease states. Several studies have highlighted the utility of 3D-printed models in the training and education of residents, fellows, and engineers. [15] The clinical goal of vascular model development is to improve patient safety by helping physicians acquire and maintain the necessary interventional skills. With new model manufacturing techniques, we need to examine the physical properties of 3D-printed models and understand the capabilities and limitations of the existing materials and manufacturing techniques so that expectations and conclusions from their use are framed accordingly.

The accuracy of the 3D-printed hollow model requires a high-quality 3D printer and CAD data. Although the accuracy of the Form3 printer has been reported, [16, 17] there are few reports on creating CAD data. The hollow application is required to create a cerebral aneurysm model with an STL printer. The Autodesk Meshmixer (Autodesk, San Rafael, California, USA) is most often used to create CAD data. [8] This software is useful when targeting a large object such as a skull or femoral bone, but it is more difficult to target smaller structures such as an intracranial aneurysm and vessels. [18] Small vessels can appear occluded due to the thickening of the blood vessel wall more than its normal anatomy. [8 9] Hence, small vessels such as the ophthalmic artery, the posterior communicating artery, and the anterior choroidal artery need to be modified. A professional CAD application is required to convert STL data files in detail. Medical workers are used to dealing with DICOM but not STL data. Since 3DDSA data are vessel lumen data, it is necessary to create a pseudo-vascular vessel wall. Therefore, we applied the WC technique, which was originally reported as a method to identify gastric cancer. [10] The WC technique can enhance the gastric wall at an arbitrary depth from the same viewpoint as optical endoscopy or fluoroscopy, which can be evaluated by interpreters at a glance. [11] Using this technique, it was possible to create distal main vessels, such as the middle cerebral artery or anterior cerebral artery, small vessels, or aneurysm walls as thin as 0.2 mm. To the best of our knowledge, there are no reports of a technique to create a thin vessel or aneurysm wall. The intracranial carotid artery and middle cerebral artery wall were 0.4 mm and 0.2 mm, respectively, which are anatomically matched. [12] The vessel walls of small vessels such as ophthalmic arteries are less than 0.2 mm, but it was difficult to reproduce vessel walls thinner than this. Moreover, small vessels, such as the ophthalmic artery or fenestration of the anterior cerebral artery, were reproduced. Our method can produce about 10 models in one printout in ten hours. Models can be made up to 15 cm x 15 cm in size. The cost of one model is about $1.

The Dice coefficient index was used for shape analysis after image registration. In image studies that used the Dice coefficient index to compare images, values greater than 70% were considered to indicate acceptable performance. In the present study, the Dice coefficient index values ranged from 88.7% to 97.3% (mean, 93.6% ± 2.5%), indicating a high level of accuracy.

This study has some limitations. First, the sample size and the number of people measured are small. Second, for example, an arterio-venous malformation model cannot be created because it is impossible to preserve vessels of 100 μm or less. We did not confirm whether model creation is possible with other 3D printers. In addition, we used the WC technique with Ziostation2, but not with other image workstations. We plan to examine the technique using other 3D printers in the future. Finally, a new verification method is needed to prove that the model is more accurate and superior to the already reported hollow model.

The final aim of this study was to develop accurate vascular models to improve neuroendovascular treatments. The variability of vascular anatomy requires individual treatment planning using preoperative simulations with 3D-printed hollow models. This study confirmed that the shape of our 3D-printed hollow models is very accurate. Therefore, neuroendovascular surgeons can obtain behavioral feedback from simulations of the use of embolic agents, such as coils and *N*-butyl-2-cyanoacrylate, in the vasculature. Accordingly, we believe that the WC technique will lay the foundation for future developments in this area. We plan to use 3D-printed hollow models in clinical practice, as we have described, and assess their usefulness in preoperative simulation for the endovascular treatment of intracranial aneurysms.

Conclusion

The WC technique describes the contrast enhancement of intracranial vessels and aneurysms at arbitrary depths in detail. This method demonstrated that small intracranial vessels and aneurysms can be physically reproduced from a patient's 3DDSA as a 3D-printed model, which could have useful surgical and educational applications. Measuring vessels with a diameter of less than 100 μm requires further work to assess and increase confidence in 3D model reproduction. Further investigations need to be conducted to accurately replicate the details of anatomically closed intracranial vascular disease.

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Competing interests

None declared.

Contributors

All authors contributed to the conception, data gathering, and drafting of the manuscript, along with manuscript oversight and administrative support. All authors critically reviewed the manuscript and approved its final submission.

References

1. Pucci JU, Christophe BR, Sisti JA, et al. Three-dimensional printing: technologies, applications, and limitations in neurosurgery. *Biotechnol Adv* 2017;35:521-29. doi: 10.1016/j.biotechadv.2017.05.007 [published Online First: 2017/05/30]
2. Langridge B, Momin S, Coumbe B, et al. Systematic Review of the Use of 3-Dimensional Printing in Surgical Teaching and Assessment. *J Surg Educ* 2018;75:209-21. doi: 10.1016/j.jsurg.2017.06.033 [published Online First: 2017/07/22]
3. Sugiu K, Martin JB, Jean B, et al. Artificial cerebral aneurysm model for medical testing, training, and research. *Neurol Med Chir (Tokyo)* 2003;43:69-72; discussion 73. doi: 10.2176/nmc.43.69 [published Online First: 2003/03/12]
4. Dholakia RJ, Kappel AD, Pagano A, et al. In vitro angiographic comparison of the flow-diversion performance of five neurovascular stents. *Interv Neuroradiol* 2018;24:150-61. doi: 10.1177/1591019917748317 [published Online First: 2017/12/15]
5. Wurm G, Tomancok B, Pogady P, et al. Cerebrovascular stereolithographic biomodeling for aneurysm surgery. Technical note. *J Neurosurg* 2004;100:139-45. doi: 10.3171/jns.2004.100.1.0139 [published Online First: 2004/01/28]
6. Kaneko N, Mashiko T, Ohnishi T, et al. Manufacture of patient-specific vascular replicas for endovascular simulation using fast, low-cost method. *Sci Rep* 2016;6:39168. doi: 10.1038/srep39168 [published Online First: 2016/12/16]
7. Ho D, Squelch A, Sun Z. Modelling of aortic aneurysm and aortic dissection through 3D printing. *J Med Radiat Sci* 2017;64:10-7. doi: 10.1002/jmrs.212 [published Online First: 2017/01/31]
8. Izzo RL, O'Hara RP, Iyer V, et al. 3D Printed Cardiac Phantom for Procedural Planning of a Transcatheter Native Mitral Valve Replacement. *Proc SPIE Int Soc Opt Eng* 2016;9789 doi: 10.1117/12.2216952 [published Online First: 2016/02/27]
9. Knox K, Kerber CW, Singel SA, et al. Stereolithographic vascular replicas from CT scans: choosing treatment strategies, teaching, and research from live patient scan data. *AJNR Am J Neuroradiol* 2005;26:1428-31. [published Online First: 2005/06/16]
10. Tsurumaru D, Kawanami S, Komori M, et al. Prediction of intraoperative bleeding during endoscopic treatment in patients with early gastric cancers: utility of contrast-enhanced MDCT gastrography and the wall-carving image technique. *Jpn J Radiol* 2013;31:237-42. doi: 10.1007/s11604-012-0172-6 [published Online First: 2012/12/19]
11. Tsurumaru D, Nishimuta Y, Muraki T, et al. CT gastrography wall-carving technique of gastric cancer: impact of contrast enhancement based on layer depth. *Jpn J Radiol* 2019;37:597-604. doi: 10.1007/s11604-019-00845-z [published Online First: 2019/06/10]
12. Harteveld AA, Denswil NP, Van Hecke W, et al. Ex vivo vessel wall thickness

measurements of the human circle of Willis using 7T MRI. *Atherosclerosis* 2018;273:106-14. doi: 10.1016/j.atherosclerosis.2018.04.023 [published Online First: 2018/05/02]

13. Shibata E, Takao H, Amemiya S, et al. 3D-Printed Visceral Aneurysm Models Based on CT Data for Simulations of Endovascular Embolization: Evaluation of Size and Shape Accuracy. *AJR Am J Roentgenol* 2017;209:243-47. doi: 10.2214/ajr.16.17694 [published Online First: 2017/07/22]
14. Frölich AM, Spallek J, Brehmer L, et al. 3D Printing of Intracranial Aneurysms Using Fused Deposition Modeling Offers Highly Accurate Replications. *AJNR Am J Neuroradiol* 2016;37:120-4. doi: 10.3174/ajnr.A4486 [published Online First: 2015/08/22]
15. Waqas M, Mokin M, Lim J, et al. Design and Physical Properties of 3-Dimensional Printed Models Used for Neurointervention: A Systematic Review of the Literature. *Neurosurgery* 2020;87:E445-53. doi: 10.1093/neuros/nyaa134 [published Online First: 2020/05/12]
16. Mitsuoka H, Terai Y, Miyano Y, et al. Preoperative Planning for Physician-Modified Endografts Using a Three-Dimensional Printer. *Ann Vasc Dis* 2019;12:334-39. doi: 10.3400/avd.ra.19-00062 [published Online First: 2019/10/23]
17. Torres I, De Luccia N. Artificial vascular models for endovascular training (3D printing). *Innov Surg Sci* 2018;3:225-34. doi: 10.1515/iss-2018-0020 [published Online First: 2018/08/11]
18. Ho M, Goldfarb J, Moayer R, et al. Design and Printing of a Low-Cost 3D-Printed Nasal Osteotomy Training Model: Development and Feasibility Study. *JMIR Med Educ* 2020;6:e19792. doi: 10.2196/19792 [published Online First: 2020/11/18]

Table

Table 1

Aneurysm diameter and volume based on patient 3DDSA data and 3D-printed hollow models

Aneurysm volumes were calculated as follows: volume = $4/3\pi \times (a/2) \times (b/2) \times (c/2)$, where a, b, and c denote the aneurysm height, length, and width (expressed as millimeters),

Case	Location	Patient Data				3D-printed Model Data				Volume Difference (mm^3)	Percentage Volume Difference	Dice Coefficient Index (%)
		Diameter (mm)			Volume (mm^3)	Diameter (mm)			Volume (mm^3)			
		a	b	c		a	b	c				
1	ICA-ophthalmic	4.0	5.9	3.1	38.3	4.0	6.0	3.2	40.2	−1.9	−5.0	91.2
2	IC-PC	5.1	5,1	2.7	36.8	5.1	5.1	2.7	34.1	2.7	7.3	88.7
3	ICA-A ChoA	10.1	12.9	6.9	470.9	10.3	12.7	6.8	465.9	5.0	1.1	92.6
4	AcomA	3.6	6.3	4.1	48.7	3.6	6.4	4.1	49.5	−0.8	−1.6	93.4
5	MCA	11.8	13.8	11.6	989.3	11.6	13.9	11.6	979.6	9.7	1.0	96.3
6	BA top	6.4	8.0	6.4	171.6	6.3	8.0	6.4	168.9	2.7	1.6	95.2
7	ICA-Cav	9.5	17.1	10.8	918.9	9.4	16.9	11.0	915.2	3.7	0.4	97.3
8	ICA-Cav	17.1	29.9	16.9	4525.6	17.1	30.1	17.1	4609.8	−84.2	−1.9	93.6
9	ICA-Cav	16.9	16.9	12.4	1854.9	16.8	17.1	12.2	1835.6	19.3	1.0	94.7

respectively. The volume difference was calculated as follows: volume in patient data minus volume in model data. The percentage volume difference was calculated as follows: (difference in volume/volume in patient data) × 100.

Figure Legends

Figure 1

Concept of the wall-carving image of an intracranial aneurysm. The upper row presents illustrations, and the lower row presents multi-planar reconstruction (MPR) images. (a) Original image of the MPR of 3D digital subtraction angiography. The red area shows the aneurysm lumen and parent artery filled with contrast medium. (b) The segmented target of the contrast medium lumen was expanded at arbitrary voxels. Each arrow shows an enlargement of the original image. (c) The figure obtained by subtracting the original figure (a) from the expanded figure (b) is the vessel wall.

Figure 2

The method of preserving the small branches and the aneurysm. (a) Original image of the volume rendering of three-dimensional digital subtraction angiograms. (b, c) The aneurysm and small vessels are separated from the parent artery. (d, e) The wall-carving technique is used to set each vessel wall to a thickness of 0.2 or 0.4 mm. (f) Each wall-carving image is added.

Figure 3

Sample aneurysm geometries. 3D rotational angiography demonstrates an ICA ophthalmic aneurysm (Case 1) and a giant fusiform ICA-Cav aneurysm (Case 8). Patient anatomy (a and c) and corresponding vascular models (b and d) are shown.

Figure 4

Sample aneurysm 3D-printed model (Case 1). (a, b) The 3D-printed model connected to the perfusion system. The microguidewire and microcatheter were placed in the aneurysm of the model.

(c) Unsubtracted image of microguidewire and microcatheter placement in the aneurysm (arrow).