Vol.65: e22210575, 2022
https://doi.org/10.1590/1678-4324-2022210575
ISSN 1678-4324 Online Edition

Article - Engineering, Technology and Techniques

Experience in Using Additive Manufacturing of Cerebral Aneurysms as a 3D Assistant Tool in Surgical Planning

Lorena Maria Dering[1,2*]
https://orcid.org/0000-0001-8540-7851

Matheus Kahakura Franco Pedro[1,2]
https://orcid.org/0000-0003-1166-9722

Ana Carolina Felipe da Silva[2]
https://orcid.org/ 0000-0001-5098-056X

André Giacomelli Leal[2]
https://orcid.org/0000-0002-1001-6431

Mauren Abreu de Souza[1]
https://orcid.org/0000-0001-6137-918X

[1]Pontifícia Universidade Católica do Paraná, Programa de Pós graduação em Tecnologia em Saúde, Curitiba, Paraná, Brasil; [2]Instituto de Neurologia de Curitiba, INC 3D Technology Lab, Curitiba, Paraná, Brasil.

Editor-in-Chief: Alexandre Rasi Aoki
Associate Editor: Alexandre Rasi Aoki

Received: 02-Sep-2021; Accepted: 28-Mar-2022.

*Correspondence: lorenadering@gmail.com; Tel.: +55-41-3028 9570 (L.D.)

HIGHLIGHTS

- The use of 3D models in medicine brings several advantages in the medical field.
- AM is useful for the patient's understanding of the disease.
- AM is a fast and low-cost option to produce patient-specific AI models that can be used for surgical planning.

Abstract: Additive manufacturing (AM) is being increasingly disseminated in several areas of knowledge. In medicine, the use of 3D models arrived to facilitate diagnoses, assist in the assessment of pathological changes, in the training of new professionals, and patient-specific anatomical 3D visualization. This study aimed to perform a rapid and low-cost additive manufacturing of patient-specific intracranial aneurysms to facilitate anatomical visualization of the aneurysms. For this purpose, patient-specific models were manufactured in an FDM 3D printer from DICOM images of CT angiography or digital subtraction angiography. We obtained 15 models of intracranial aneurysms, with different sizes and geometries, which were used by neurosurgeons as part of the surgical planning of each case. AM is a quick and low-cost option to produce patient-specific AI models; however, further studies are still required to improve the technique.

Keywords: 3D Printing; Intracranial Aneurysm; Neurosurgery.

INTRODUCTION

Additive manufacturing (AM), more known as "3D printing", was created as a fast method of prototyping in the industry. Taking into consideration the technological advances and easier equipment acquisition, the AM are currently included in the most diverse areas, including medical services [1–4]. Since its introduction in the late 1980s, it became possible to use AM to produce drugs, biocompatible implants, medical models (such as orthoses and prostheses), equipment, components, and a variety of customized medical devices [5,6].

According to Aimar and coauthors, 2019 [7], for manufacturing medical models, five main steps are followed: (A) selection of the anatomical area; (B) 3D geometry development from medical image processing; (C) file optimization; (D) proper selection of printer and material to be used, and (E) post-processing. This production process is based on the modalities of medical images that provide imaging slices, such as magnetic resonance images (MRI) and computed tomography (CT) [4]. In addition to these modalities, other options for AM have already been described, including ultrasound, and Digital Subtraction Angiography (DSA) [6].

It has already been described by Abdullah & Reed [6], that the use of 3D models in medicine facilitates diagnosis and assists in the assessment of pathological changes; the training of new professionals; and the anatomical visualization of patient-specific organs or tissues, outlining peculiar interventions [8]. Furthermore, as it is a fast process for manufacturing biological models, it is possible to reduce healthcare costs, for example, the use of customized and low-cost implants and prosthetics, which saves significant value for the patient [9]. According to Martelli and coauthors, 2016 [10], several studies have already pointed to AM as a useful tool to reduce time in operating rooms, such as Nadagouda, 2020 [11].

In the literature, there are reports on the use of AM to manufacture models of intracranial aneurysms (IA), vascular lesions characterized by areas of weakness in the arterial wall, which promote sacculation growth. These aneurysms are usually found in arterial bifurcations and the anterior circulation of the circle of Willis. When ruptured, AIs, can lead to subarachnoid hemorrhage, with high rates of morbidity and mortality [12,13].

Leal and coauthors (2019) described the use of AM for the creation of flexible AI biomodels for planning aneurysm clipping from CT angiography exams. It was observed that with such models it is possible to simulate the use of materials in surgery, making the actual surgery faster and with better results [14]. A similar model was also described by Mashiko (2017), as a proposal for training new surgeons [15].

Recently, the use of AM for making medical models of IA is becoming more widespread, such as: (1) it facilitates the patient's understanding of the location of the aneurysm, (2) the designated treatment, what interventions and results are expected; and (3) it helps neurosurgeons in the pre-operative planning and intra-operative understanding [16]. Very recent examples of the use of 3D printing for neurosurgical approaches are mentioned, such as Xu and coauthors, 2020 [17], which presented the use of 3D printed models for intracranial aneurysm coiling, making the aneurysm embolization procedure more efficient and precise. Also, Marciuc and coauthors, (2021) [2] described positive results, especially for junior neurosurgeons, that were capable to see the vessel's anatomy with a better perspective, with the use of these real models for the three-dimensional visualization of aneurysms in treatment planning. In addition to planning IA clipping surgeries, it is already possible to use AM to produce training models for endovascular surgeries, even simulating the patient's hemodynamics [3].

So, the literature has already been presenting promising results in the use of 3D printing in surgical planning. Therefore, this study presents the generation of 3D real models of fifteen case studies, based on patient-specific intracranial aneurysms, which employed rapid and low-cost additive manufacturing techniques, with the aim of facilitating anatomical 3D visualization of aneurysms that were used for planning surgical purposes and for training by neurosurgeons.

MATERIAL AND METHODS

This study was first approved by the Human Ethics Committee of the Institute of Neurology of Curitiba (CEPSH-INC) under protocol number 4.467.491-2020. All patients signed the Informed Consent Form, authorizing the use of imaging exams. The whole process involves several steps, which are described as follows:

(A) Imaging Acquisition

First, the cerebral aneurysms patients were submitted to the imaging acquisition, which was based on two types: (1) CT angiography, obtained in a General Electric Optima® (Figure 1) and (2) 3D Rotational

Digital Subtraction Angiography (DSA) using a Philips Allura XPerFD 20 equipment (Figure 2). The imaging format of both modalities is in DICOM (Digital Imaging and Communications in Medicine).

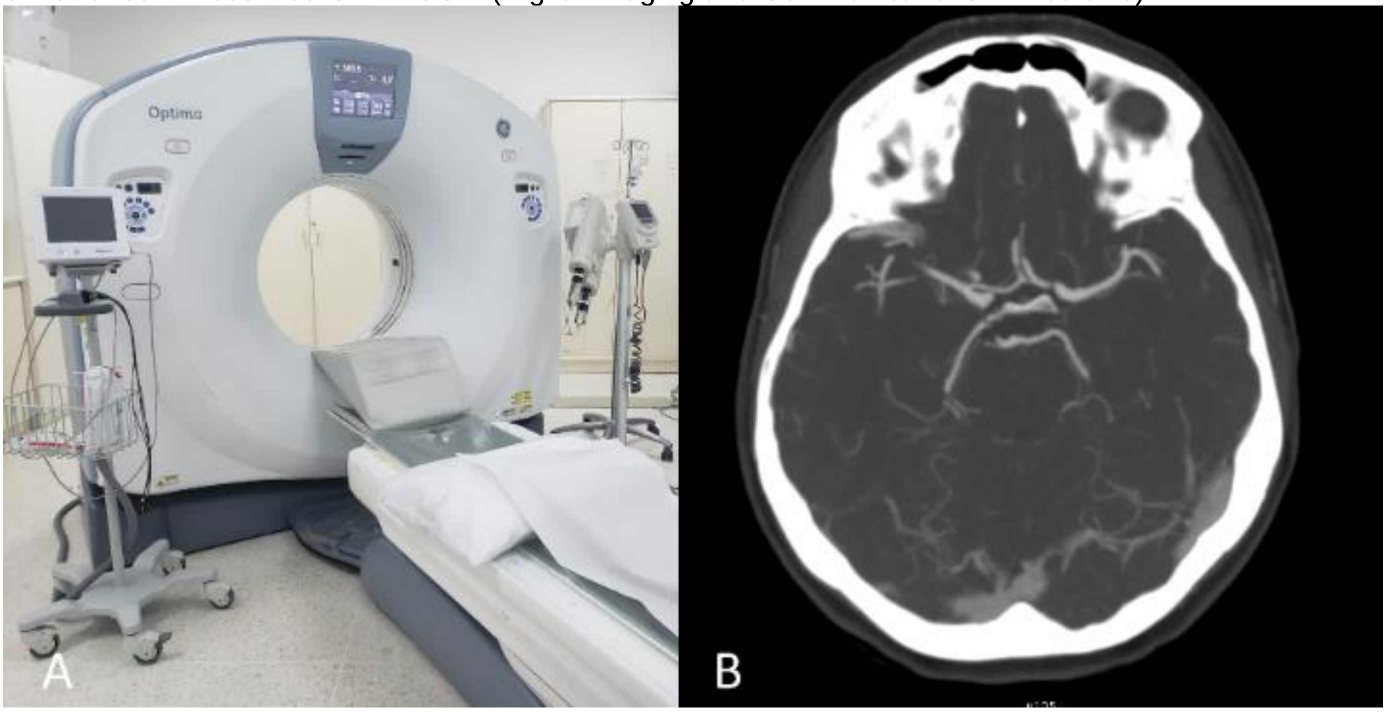

Figure 1. (A) CT General Electric Optima®; and (B) A sample of the DICOM 2D image acquired by this equipment.

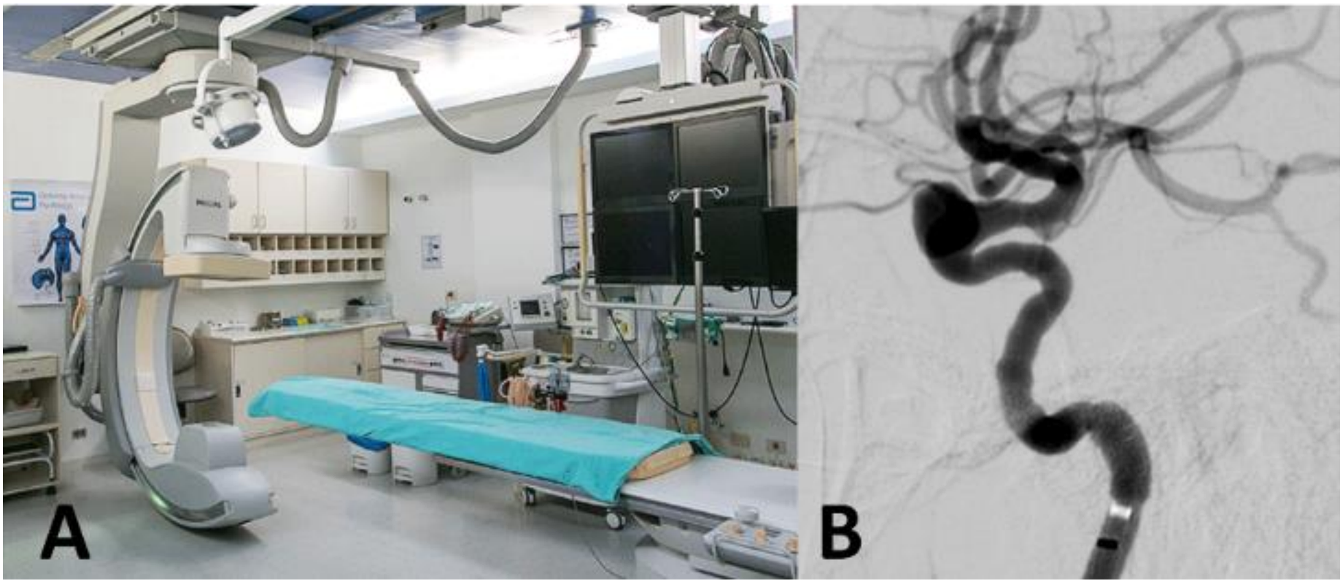

Figure 2. (A) 3D Rotational Digital Subtraction Angiography (DSA) using a Philips Allura XPerFD 20 equipment; and (B) A sample of the DICOM 2D image acquired by this equipment.

(B) Imaging Processing

For this step, the imaging segmentation of the IA structures was made in the software 3D Slicer, version 4.11.20200930, a free and open-source software, certified for medical use. For this purpose, the DICOM files were obtained from the imaging modalities (CT angiography or DSA) and imported into the software (Figure 3). It was used the segment editor tools, which are mainly used for selecting and extracting the region of interest (i.e., the main artery with the IA) from the other structures.

After the initial segmentation, using the 3D Slicer software, it was generated the virtual 3D digital models from the DICOM images (Figure 4A). In this case, the selected area was the artery with the aneurysm. The 3D model generated went through a cleaning process, resulting in the 3D reconstruction of the area of interest (Figure 4B).

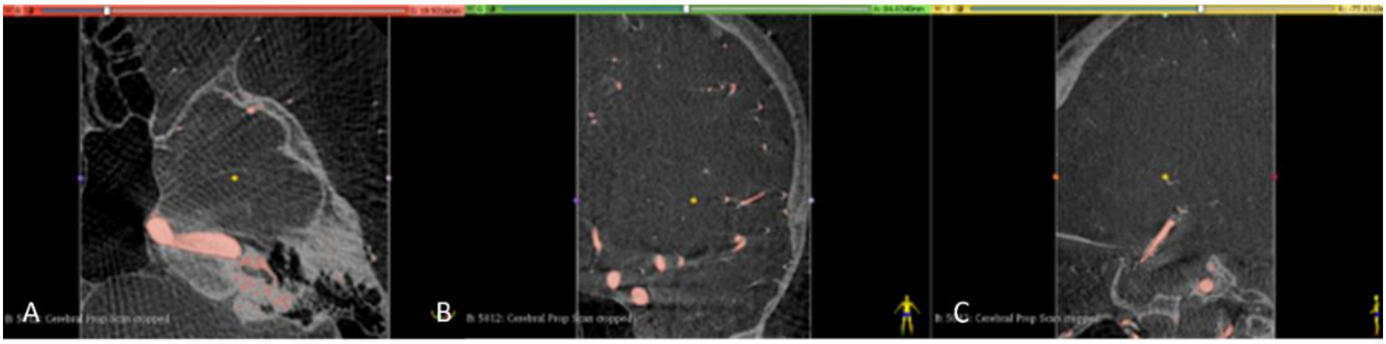

Figure 3. DICOM images from DAS in the 3D Slicer® software. (A) Axial, (B) coronal, and (C) sagittal cuts. A mask is applied according to the threshold of the area of interest, thus generating the 3D model of the artery and aneurysm.

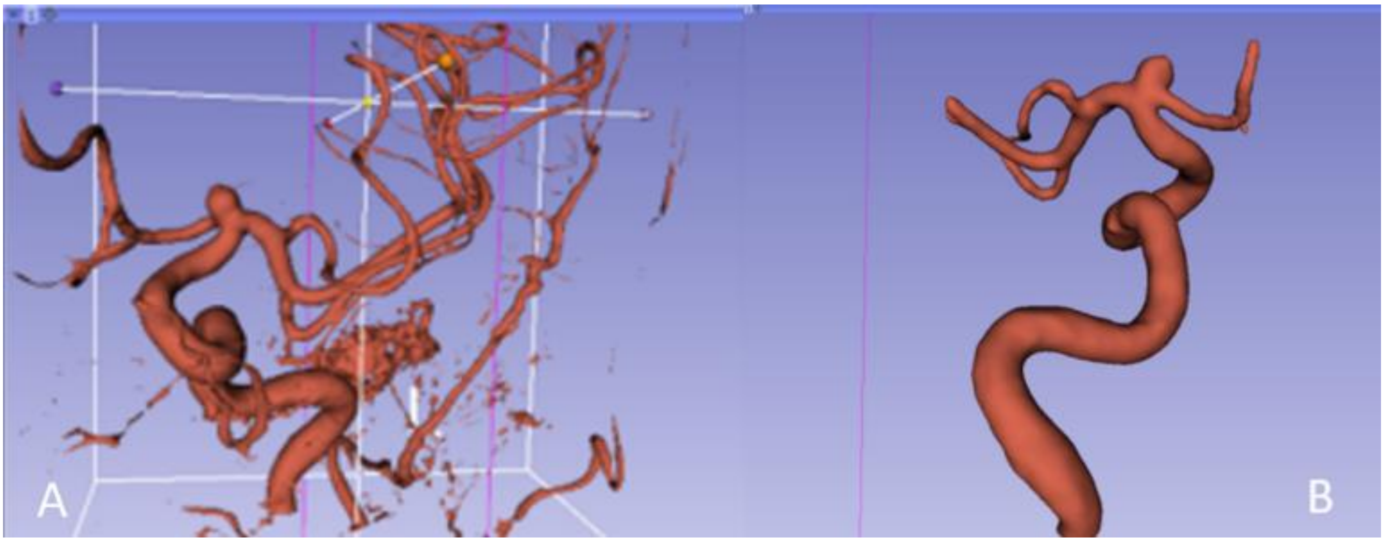

Figure 4. (A) The Generation of the form of the mask. (B) 3D model after cleaning the areas that are not needed. This is the final file, which will be sent to the Ultimaker Cura® software for AM.

(C) 3D Printing

The next step is the 3D printing, which was based on the actual manufacture, i.e., the 3D virtual model to be sent to the equipment (3D printer). For this, the Ultimaker Cura® Version 4.9.1 software was used to prepare the virtual model for the AM (Figure 5A). In this step, the printing parameters are chosen: a layer thickness of 0.12 mm, as it results in better printing resolution; a printing speed of 30 mm/s; and a printing temperature between 200 – 226 ºC, depending on the material. In this study was used an FDM (Fused Deposition Modelling) printer, a CR5-PRO (Creality) (Figure 5B), with Two types of filaments: PLA (polylactic acid) for five cases and ABS (acrylonitrile butadiene styrene) for the remaining cases. The choice of material was random.

Further details need to be considered, especially when dealing with printing complex models. In this case, it is necessary to use supports for the workpiece; for this reason, post-processing was also carried out, removing the supporting structures, and finishing the printed models by sanding or shining with acetone vapor.

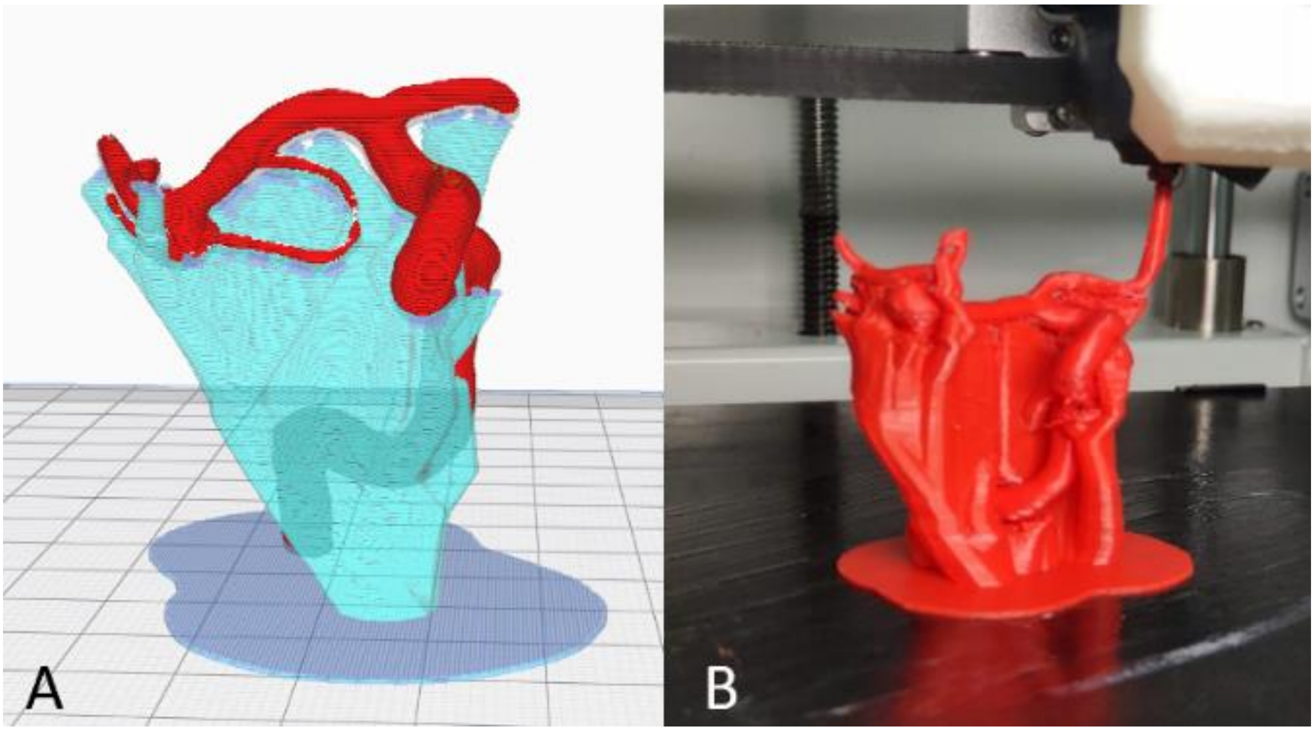

Figure 5. (A) The model in the Cura® software, ready for printing, and (B) the model being printed.

(D) Clinical Evaluation

As a final step, the generated 3D models were used for training surgical planning and for teaching junior neurosurgeons and interns. Therefore, neurosurgeons used the model to plan the type of clip that would be used for aneurysm clipping surgery.

RESULTS

Overall, between January and June 2021, 15 cases of AIs with different characteristics (size, location, and segments) were manufactured, according to Table 1. These clinical parameters are used for the selection of the aneurisms:

(a) Size - indicates the size of the aneurysm neck versus the neck-dome distance, respectively.

(b) Location – it represents the artery where the IA was located. All the models were selected from saccular aneurysms, as divided: 4 were from Internal Carotid Artery (ICA), 7 from Middle Cerebral Artery (MCA), 3 from the Anterior Communicating Artery (ACoA), and 1 from Choroid Artery (CA).

(c) Segment – some of the intracranial arteries are divided into segments, to facilitate the localization, so the portion of the artery that contains the aneurysm is indicated for the segment.

Table 1. Characteristics of the data of the manufactured aneurysms: Size, location, and segment.

Case	Size (mm)	Location	Segment
01	4.5 x 6.0	ICA	Segment C4
02	3.7 x 2.9	MCA	Bifurcation
03	5.1 x 4.5	MCA	Bifurcation
04	4.9 x 4.4	MCA	Trifurcation
05	4.1 x 2.1	ACoA	-
06	2.4 x 2.8	MCA	Bifurcation
07	2.8 x 7.6	ICA	Segment C7
08	4.6 x 6.8	ACoA	-
09	2.7 x 3.2	CA	-
10	4.4 x 5.9	MCA	Bifurcation
11	3.4 x 4.6	ACoA	-
12	6.1 x 3.0	MCA	Bifurcation
13	6.5 x 15.7	ICA	Segment C4
14	1.8 x 4.0	MCA	Bifurcation
15	4.1 x 4.0	ICA	Bifurcation

Additionally, printing characteristics such as costs, and printing time, were collected and presented in Table 2. The time of each manufactured 3D model varied according to the size of the artery (as presented in Table 1). The average cost of manufacturing the models was US$ 2.15; this value also includes the timing costs for designing the 3D models.

Table 1: Printing characteristics of the manufactured aneurysms.

Case	Printing Time (minutes)	Costs (US$)
1	174	2.19
2	165	2.19
3	119	2.14
4	123	2.12
5	111	2.11
6	94	2.08
7	240	2.17
8	113	2.11
9	131	2.12
10	124	2.12
11	195	2.21
12	137	2.15
13	135	2.15
14	160	2.19
15	131	2.14

Of all these 15 3D generated models, only 2 cases were produced from CT angiography exams, and 13 models were from DSA. Also, it was used two different types of filaments (materials): ABS and PLA (Figures 6 and 7).

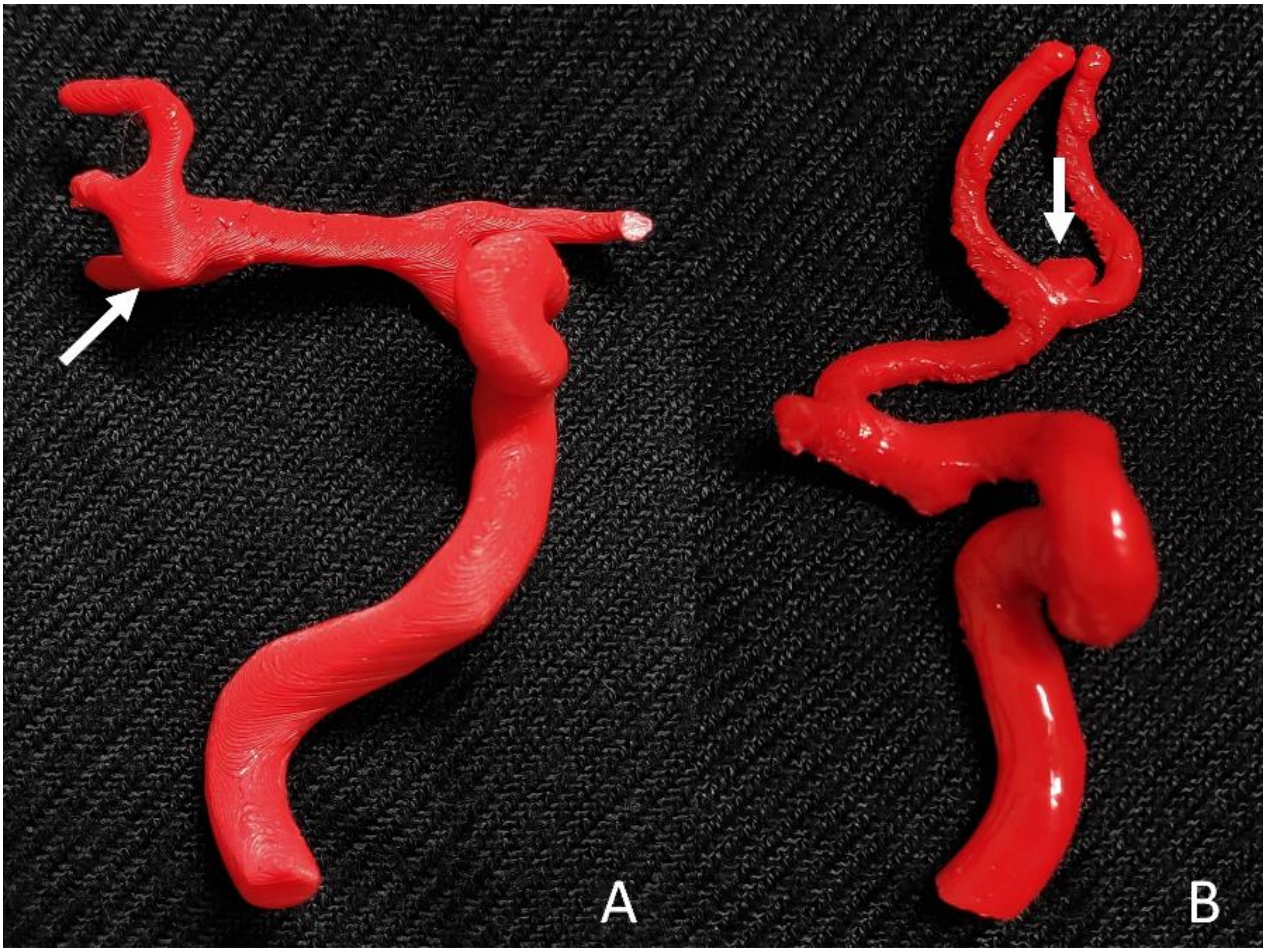

Figure 6. Models of aneurysms manufactured in ABS. (A) ACM trifurcation aneurysm, measuring 4.9x4.4 mm, and (B) ACoA aneurysm, measuring 4.1x2.1 mm.

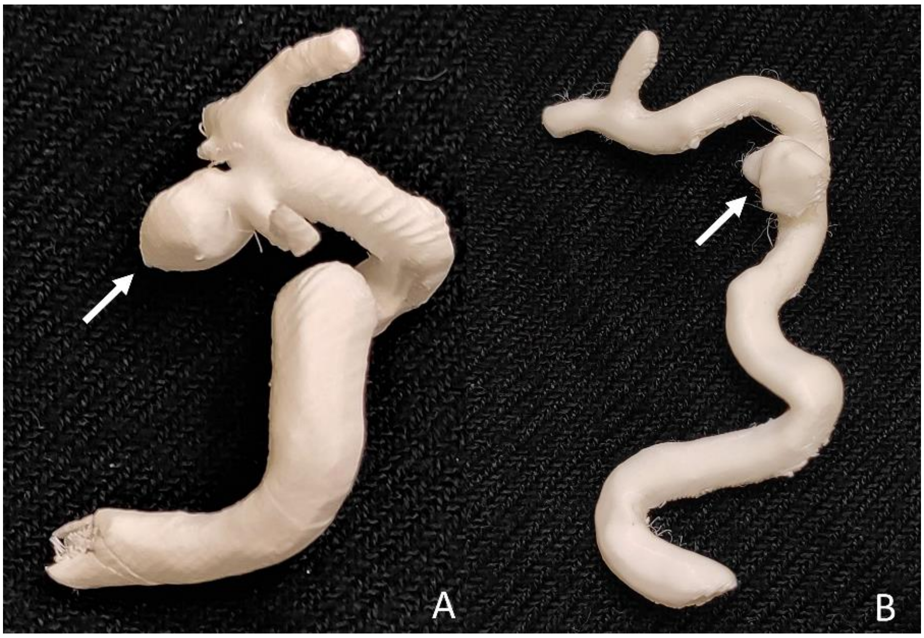

Figure 7. Aneurysm models made of PLA material. (A) Aneurysm located in the C7 segment of the ICA, measuring 2.8 x 7.6 mm. (B) ACI C4 segment aneurysm, measuring 4.5 x 6 mm.

After finalizing the AM and its correspondent post-processing (which involves removing the supporting structures, sanding the model, and bathing in acetone vapor, when necessary); then, as a final step of this research, the models were used by neurosurgeons for visualization and planning the respective surgeries. In Figure 8, it is possible to visualize one of the 3D models, from an MCA aneurysm, which is compared to one of the 2D images from the ASD imaging modality. Here we highlight the advantage of using the AM enabling three-dimensional visualization and through the physical model (real) in the region under inspection regarding the use of a collection of two-dimensional images (DICOM) file formats.

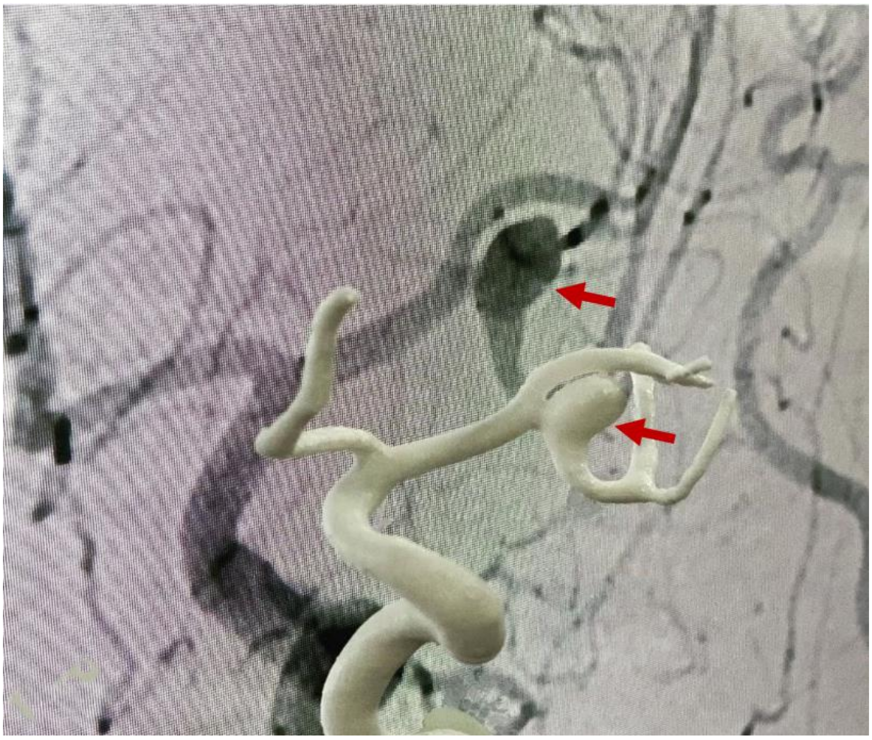

Figure 8: MCA cerebral aneurysm 3D model compared to ASD examination. Arrows indicate the aneurysm in the model and DICOM image.

As a result of the use of the models for surgical planning, table 3 shows the type of clip chosen in the planning vs the type of clip implanted. The correspondences show that the models can be useful for optimizing surgeries, with prior planning.

Table 2. Type of clip chosen in the planning vs the type of clip implanted.

Case	Planning	Implanted	Matches
1	bayonet	bayonet	Yes
2	curved	bayonet	No
3	straight	straight	Yes
4	straight	straight	Yes
5	bayonet	bayonet	Yes
6	bayonet	straight	No
7	bayonet	bayonet	Yes
8	curved	curved	Yes
9	straight	straight	Yes
10	straight	curved	No
11	bayonet	bayonet	Yes
12	straight	curved	No
13	bayonet	bayonet	Yes
14	straight	curved	No
15	curved	curved	Yes

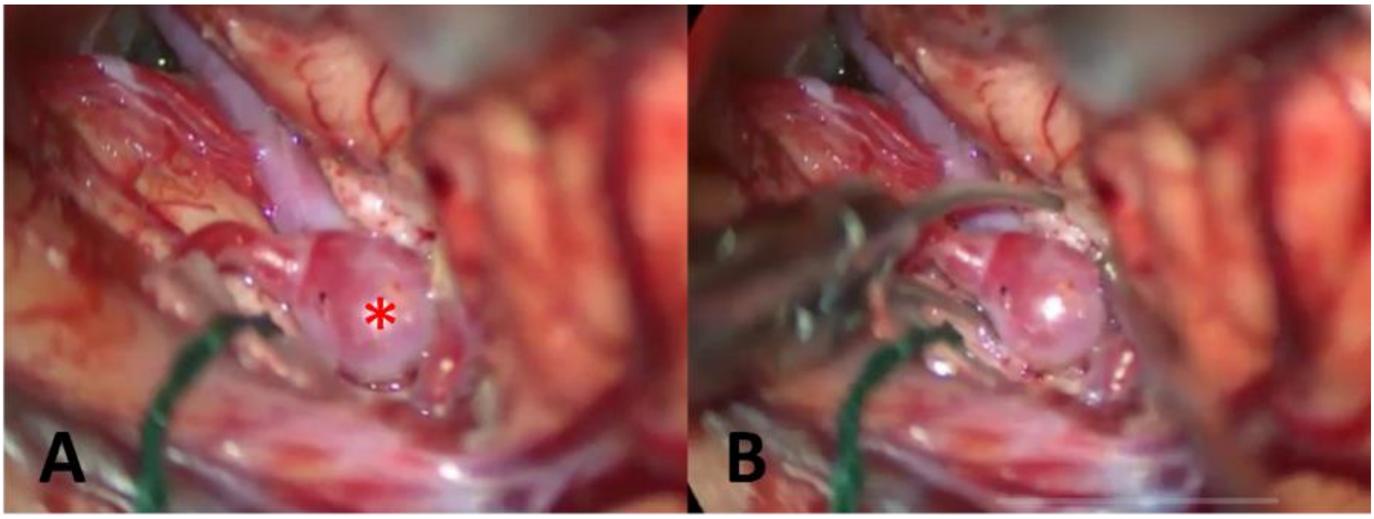

Figure 6. (A) Surgical view of the MCA aneurysm (asterisk) presented in Figure 7, left frontotemporal approach. (B) The clip is being placed.

DISCUSSION

This study aimed to demonstrate the 3D printing of patient-specific models of IA, using an FDM 3D printer for the anatomic visualization enabling better surgical planning. Models of aneurysms with different locations, sizes, and geometries were made, illustrating that it is possible to perform this type of AM in-hospital.

Different AM applications in the medical field have been growing, due to the possibility of personalized models [18]. In addition to surgical planning, AM is useful for the patient's understanding of the disease: the use of AI models has been shown to be more effective in aiding the patient's understanding when compared to traditional methods, such as two-dimensional ASD imaging. Thus, patients feel better informed about the processes that involve the surgery [19].

From this perspective, the models of this study were used to demonstrate to patients, in a three-dimensional view, what aneurysms are and how the treatment would be performed. Neurosurgeons who used the models reported a positive response from patients when approached in this way. Other studies [2,3,17] had reported positive results in the use of IA models to improve the treatment, including decision-making on which treatment to choose, microsurgery, or endovascular therapy [20].

According to Leal and coauthors, 2021 [21], it is commonly difficult to choose the appropriate clip to be used, due to the anatomical variabilities of each aneurysm. Moreover, surgical planning is essential to avoid excessive manipulation of the intracranial vessels and an extended surgical time, which can predispose to aneurismatic rupture. Therefore, preoperative planning in touchable/flexible models that reproduce the surgical anatomy is helpful. Given that, some studies reported that the biomodels were anatomically precise when compared to the real anatomy of the patient, acquired through images of the ASD.

The choice of the models in surgical planning, when compared with the models that were implanted, shows promising results, although not all clips correspond to the same implanted clips. This can be a result of the type of material used, i.e., a rigid plastic, without the same properties as the artery. Leal and coauthors, 2019 [14] demonstrated with a flexible material, that all the clips chosen in the surgical planning were the same as those used during the surgery (i.e., there was a matching among them).

Besides that, the models were also taken to the operating room, and the neurosurgeons used them to study techniques to access the aneurysm and perform the clipping. Additionally, also in the operating room, the models were useful for residents and interns to visualize the aneurysm that would be operated, as reported in the literature as a very useful tool for learning [15,22–24].

Within our results, despite the models' similarity to real IAs, one of the limitations of the models is the stiffness of the printed material, as the arteries are flexible. However, this did not influence the final aim of the generation of the model, which was the anatomical 3D visualization of the aneurysm for surgical planning and training of junior neurosurgeons. Furthermore, the same methodology can be used to create flexible and lumen models, covering the models with silicone rubber and dissolving the solid model in acetone, as previously described by Leal and coauthors, 2019 [14] and Mashiko and coauthors, 2017 [15].

Another limitation of the study is the size of the vessels since there is a constraint for making arterial branches smaller than 1 mm in diameter. As confirmed by Frölich and coauthors, 2016 [24], this is one of the main limitations of AM by FDM. The 3D printing via FDM is a lengthy process because, besides the rendering of the object, it involves the construction of this layer by layer. However, with AM technologies increasingly developed and accessible, production times and costs are also being reduced [22–27]. In this study, the models were produced in approximately 3h 30min after image acquisition. On average, 1 hour is used for designing the models and the rest for printing, which is enough time to produce models for unruptured aneurysm clipping surgeries. When compared to other authors, the production time was shorter; for example, Erbano and coauthors (2013) [20] reported the AM of AI using a polyjet type printer, in which each model had a production time of about 20 hours (on average). However, in a more recent study, also using FDM technology, Błaszczyk and coauthors, 2021 achieved a production time of approximately 4 hours, including image acquisition [27].

Regarding production costs, the models presented expenses on average of US$ 2, which amount is almost negligible compared to the other costs of the surgery, which makes it feasible to AM models for surgical planning. Apart from the materials, this value also includes the use of the printer, and the value for generating and designing such specific 3D models. The cost, as well as the time, was considered below the average described by Erbano and coauthors, 2013 [20], which costs US$130 per model. Here, it is noteworthy that the value of the product is related to the AM methodology used and the cost reduction, mainly due to the advancement of technologies. Using the same AM technology as this study, Namba and coauthors, 2015 also reported the approximate cost of US$2 per model, showing that FDM technology, despite its limitations, is probably the most affordable for AM, and, consequently, the faster way to prototype these models inside a hospital [16]. It is also necessary to consider that, despite the reduction in the operating hours, there is an increase in the total planning time with the production of the medical model. However, this time is subjective, since the costs of keeping the patient in the room can be greater than the costs of producing the model [18].

CONCLUSION

Among the most diverse possibilities, the advent of additive manufacturing made possible the production of personalized medical equipment, anatomical models, and patient-specific biomodels. The manufacture of patient biomodels is based on the acquisition of medical images, such as magnetic resonance imaging, computed tomography, and digital subtraction angiography.

It is already described in the literature that the use of patient-specific biomodels facilitates the understanding of surgeons about the area of interest, helps in teaching, and can even optimize surgeries. Therefore, this study presented a fast and low-cost option to produce patient-specific AI models that can be used for surgical planning.

The biomodels presented facilitated the visualization of the aneurysm and nearby arterial branches, and allowed the neurosurgeons to have a three-dimensional view of the aneurysm to be treated before surgery. Further studies are still needed to improve the technique, allowing the prototyping models with the lumen and even flexible, more likely human arteries.

Funding: This research received no external funding.
Conflicts of Interest: The authors declare no conflict of interest.

REFERENCES

1. Lan Q, Zhu Q, Xu L, Xu T. Application of 3D-Printed Craniocerebral Model in Simulated Surgery for Complex Intracranial Lesions. World Neurosurg [Internet]. 2020;134:e761–70. Available from: https://doi.org/10.1016/j.wneu.2019.10.191
2. Marciuc EA, Dobrovat BI, Popescu RM, Dobrin N, Chiriac A, Marciuc D, et al. 3D Printed Models—a Useful Tool in Endovascular Treatment of Intracranial Aneurysms. Brain Sci. 2021;11(5).
3. Yamaki VN, Cancelliere NM, Nicholson P, Rodrigues M, Radovanovic I, Sungur J-M, et al. Biomodex patient-specific brain aneurysm models: the value of simulation for first in-human experiences using new devices and robotics. J Neurointerv Surg [Internet]. 2021 Mar;13(3):272–7. Available from: https://jnis.bmj.com/lookup/doi/10.1136/neurintsurg-2020-015990
4. Squelch A. 3D printing and medical imaging. J Med Radiat Sci [Internet]. 2018 Sep 1;65(3):171–2. Available from: https://onlinelibrary.wiley.com/doi/10.1002/jmrs.300
5. Liaw CY, Guvendiren M. Current and emerging applications of 3D printing in medicine. Vol. 9, Biofabrication. Institute of Physics Publishing; 2017.
6. Abdullah KA, Reed W. 3D printing in medical imaging and healthcare services. Vol. 65, Journal of Medical Radiation Sciences. John Wiley and Sons Ltd; 2018. p. 237–9.
7. Aimar A, Palermo A, Innocenti B. The Role of 3D Printing in Medical Applications: A State of the Art. J Healthc Eng [Internet]. 2019 Mar 21;2019:1–10. Available from: https://www.hindawi.com/journals/jhe/2019/5340616/
8. Jamróz W, Szafraniec J, Kurek M, Jachowicz R. 3D Printing in Pharmaceutical and Medical Applications – Recent Achievements and Challenges. Vol. 35, Pharmaceutical Research. Springer New York LLC; 2018.

9. Choonara YE, du Toit LC, Kumar P, Kondiah PPD, Pillay V. 3D-printing and the effect on medical costs: a new era? Expert Rev Pharmacoecon Outcomes Res [Internet]. 2016 Jan 2;16(1):23–32. Available from: http://www.tandfonline.com/doi/full/10.1586/14737167.2016.1138860
10. Martelli N, Serrano C, Van Den Brink H, Pineau J, Prognon P, Borget I, et al. Advantages and disadvantages of 3-dimensional printing in surgery: A systematic review. Surg (United States). 2016 Jun 1;159(6):1485–500.
11. Nadagouda MN, Rastogi V, Ginn M. A review on 3D printing techniques for medical applications. Curr Opin Chem Eng [Internet]. 2020;28:152–7. Available from: https://doi.org/10.1016/j.coche.2020.05.007
12. Ajiboye N, Chalouhi N, Starke RM, Zanaty M, Bell R. Unruptured Cerebral Aneurysms: Evaluation and Management. Sci. World J. [Internet]. 2015;2015:954954. Available from: http://www.hindawi.com/journals/tswj/2015/954954/
13. Boulouis G, Rodriguez-Régent C, Rasolonjatovo EC, Ben Hassen W, Trystram D, Edjlali-Goujon M, et al. Unruptured intracranial aneurysms: An updated review of current concepts for risk factors, detection and management. Rev Neurol (Paris) [Internet]. 2017 Nov;173(9):542–51. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0035378716302855
14. Leal AG, de Souza MA, Nohama P. Additive Manufacturing of 3D Biomodels as Adjuvant in Intracranial Aneurysm Clipping. Artif Organs [Internet]. 2019 Jan;43(1):E9–15. Available from: https://onlinelibrary.wiley.com/doi/10.1111/aor.13303
15. Mashiko T, Kaneko N, Konno T, Otani K, Nagayama R, Watanabe E. Training in Cerebral Aneurysm Clipping Using Self-Made 3-Dimensional Models. J Surg Educ [Internet]. 2017 Jul;74(4):681–9. Available from: http://dx.doi.org/10.1016/j.jsurg.2016.12.010
16. Namba K, Higaki A, Kaneko N, Mashiko T, Nemoto S, Watanabe E. Microcatheter Shaping for Intracranial Aneurysm Coiling Using the 3-Dimensional Printing Rapid Prototyping Technology: Preliminary Result in the First 10 Consecutive Cases. World Neurosurg [Internet]. 2015 Jul;84(1):178–86. Available from: http://dx.doi.org/10.1016/j.wneu.2015.03.006
17. Xu Y, Tian W, Wei Z, Li Y, Gao X, Li W, et al. Microcatheter shaping using three-dimensional printed models for intracranial aneurysm coiling. J Neurointerv Surg. 2020;12(3):308–10.
18. Scerrati A, Trovalusci F, Albanese A, Ponticelli GS, Tagliaferri V, Sturiale CL, et al. A workflow to generate physical 3D models of cerebral aneurysms applying open source freeware for CAD modeling and 3D printing. Interdiscip Neurosurg Adv Tech Case Manag [Internet]. 2019;17(January):1–6. Available from: https://doi.org/10.1016/j.inat.2019.02.009
19. Kim PS, Choi CH, Han IH, Lee JH, Choi HJ, Lee J Il. Obtaining Informed Consent Using Patient Specific 3D Printing Cerebral Aneurysm Model. J Korean Neurosurg Soc [Internet]. 2019 Jul 1;62(4):398–404. Available from: http://jkns.or.kr/journal/view.php?doi=10.3340/jkns.2019.0092
20. Erbano BO, Opolski AC, Olandoski M, Foggiatto JA, Kubrusly LF, Dietz UA, et al. Rapid prototyping of three-dimensional biomodels as an adjuvant in the surgical planning for intracranial aneurysms. Acta Cir Bras [Internet]. 2013 Nov;28(11):756–61. Available from: http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0102-86502013001100002&lng=en&tlng=en
21. Leal AG, Fernandes BL, Ramina R, Henrique P, Aguiar P De. Clinical Applications of Additive Manufacturing Models in Neurosurgery : a Systematic Review Aplicações clínicas de modelos de manufatura aditiva na neurocirurgia : uma revisão sistemática. 2021;
22. Benet A, Plata-Bello J, Abla AA, Acevedo-Bolton G, Saloner D, Lawton MT. Implantation of 3D-Printed Patient-Specific Aneurysm Models into Cadaveric Specimens: A New Training Paradigm to Allow for Improvements in Cerebrovascular Surgery and Research. Biomed Res Int [Internet]. 2015;2015:1–9. Available from: http://www.hindawi.com/journals/bmri/2015/939387/
23. Liu Y, Gao Q, Du S, Chen ZC, Fu JZ, Chen B, et al. Fabrication of cerebral aneurysm simulator with a desktop 3D printer. Sci Rep. 2017;7(May):1–13.
24. Frölich AMJ, Spallek J, Brehmer L, Buhk J-H, Krause D, Fiehler J, et al. 3D Printing of Intracranial Aneurysms Using Fused Deposition Modeling Offers Highly Accurate Replications. Am J Neuroradiol [Internet]. 2016 Jan;37(1):120–4. Available from: http://www.ajnr.org/lookup/doi/10.3174/ajnr.A4486
25. Joseph FJ, Weber S, Raabe A, Bervini D. Neurosurgical simulator for training aneurysm microsurgery—a user suitability study involving neurosurgeons and residents. Acta Neurochir (Wien). 2020 Oct 1;162(10):2313–21.
26. Ionita CN, Mokin M, Varble N, Bednarek DR, Xiang J, Snyder K V, et al. Challenges and limitations of patient-specific vascular phantom fabrication using 3D Polyjet printing. In: Molthen RC, Weaver JB, editors. 2014. p. 90380M. Available from: http://proceedings.spiedigitallibrary.org/proceeding.aspx?doi=10.1117/12.2042266
27. Błaszczyk M, Jabbar R, Szmyd B, Radek M. 3D Printing of Rapid, Low-Cost and Patient-Specific Models of Brain Vasculature for Use in Preoperative Planning in Clipping of Intracranial Aneurysms. J Clin Med [Internet]. 2021 Mar 13;10(6):1201. Available from: https://www.mdpi.com/2077-0383/10/6/1201