Interdisciplinary Neurosurgery 17 (2019) 1–6

Contents lists available at ScienceDirect

Interdisciplinary Neurosurgery

journal homepage: www.elsevier.com/locate/inat

Technical Notes & Surgical Techniques

A workflow to generate physical 3D models of cerebral aneurysms applying open source freeware for CAD modeling and 3D printing

Alba Scerrati[a,*], Federica Trovalusci[b], Alessio Albanese[c], Gennaro Salvatore Ponticelli[d], Vincenzo Tagliaferri[b], Carmelo Lucio Sturiale[c], Michele Alessandro Cavallo[a], Enrico Marchese[c]

[a] *University of Ferrara, Department of Neurosurgery, Italy*
[b] *University of Rome Tor Vergata, Enterprise Engineering, Italy*
[c] *Catholic University of Rome, Department of Neurosurgery, Italy*
[d] *University Niccolò Cusano of Rome, Engineering, Italy*

ARTICLE INFO

Keywords:
Stereolitography
Cerebral aneurysms
3D printing
Surgical planning
Aneurysm models

ABSTRACT

Objectives: 3D anatomical models are becoming a new frontier in surgery for planning and simulation on an individualized patient specific basis. Since 1999, 3D cerebral aneurysms models for neurosurgery have been proposed. The possibility of reproducing in a realistic 3D fashion the malformation with the surrounding vascular structures, provides important preoperative information for the treatment strategy. The same models can be used for training and teaching.

Unfortunately stereolitography is often burdened by high costs and long times of production. These factors limit the possibility to use 3D models to plan surgeries in an easy daily fashion.

Patients and methods: Our study enrolled 5 patients harboring cerebral aneurysms. DICOM data of each aneurysm were elaborated by an open source freeware to obtain CAD molds. Afterwards, the 3D models were produced using a fused deposition or a stereolitography printer.

Results: Models were evaluated by Neurosurgeons in terms of quality and usefulness for surgical planning. Costs and times of production were recorded.

Conclusions: Models were reliable, economically affordable and quick to produce.

1. Introduction

During the last 10 years, the use of stereolitographic 3D models has been spreading in intracranial aneurysm surgery planning as a rapid prototyping technique able to reproduce complex vascular structures and providing essential preoperative information for the clipping strategy.

Ground-breaking achievements were proposed by D'Urso et al. [1] who created the first 3D biomodels for complex intracranial aneurysms and arteriovenous malformations; thereafter, Wurm et al. [2,3] improved this technique by reproducing other variables such as the cranium and the cerebral vasculature.

Many others studies [4–7] that were published since 2015, have definitely shown the undoubted accuracy and usefulness of 3D biomodels for surgical planning and training purposes. However, costs and times of production remain major issues for a widespread in clinical practice.

Since 2017, we started producing first prototypes of aneurysm 3D biomodels in our Department, recording the experience both for surgical planning, for training and for patient and family education purposes.

Here we report our experience, analyzing the utility and feasibility issues of the technique.

2. Materials and methods

From June 2017 to May 2018, 5 patients harboring intracranial aneurysms admitted to the Department of Neurosurgery of the Fondazione Policlinico Universitario A. Gemelli - IRCCS of Rome were included in the study. Construction of the 3D models included acquisition of imaging data, post-processing with object segmentation and creation of a solid model.

2.1. DICOM files conversion to Stereo-Lithographic (STL) files

DICOM data from patients' CTAs and DSAs were collected. The 3D

* Corresponding author.
E-mail address: scrlba@unife.it (A. Scerrati).

https://doi.org/10.1016/j.inat.2019.02.009
Received 24 December 2018; Received in revised form 10 January 2019; Accepted 6 February 2019

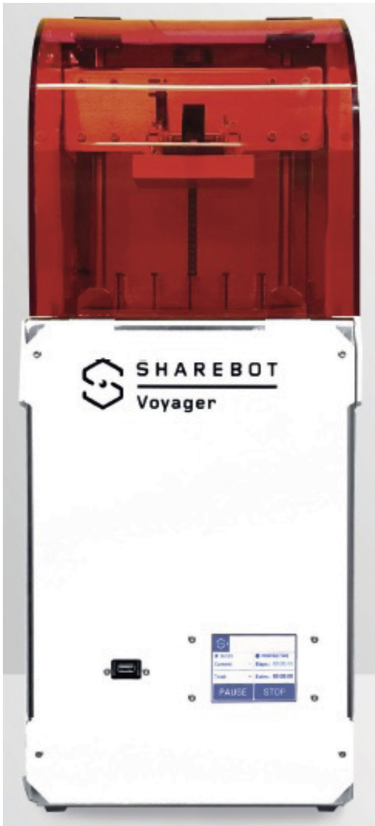

Fig. 1. ShareBot Voyager2 3D, a stereolitography (SLA) printer from Italy. The printing area is 60 × 100 × 100 mm.

DSAs were obtained with a rotational angiography using a monoplane angiograph (Philips - Allura Xper FD10).

Using 3D slicer ® or Materialise ® software the volume of the aneurysm and parent vessels was cleared from non-essential structures. Vascular structures present a particular threshold of grey pixels and this threshold was used to select the structures to be biomodelled.

SLA z-axis resolution was 0.10 mm. This process was performed both manually and automatically. The results were converted to an STL file and further elaborated for supports using Blender® or Slic3r© software.

2.2. The 3D printing process

We use two different 3D printers:

- ShareBot XXL, a fused deposition modeling (FDM) printer. It produces solid models by extruding ABS filament melted at 260 °C from a nozzle to repeatedly draw 0.10-mm thick pattern layers on a platform.
- ShareBot Voyager2 3D, a stereolitography (SLA) printer from Italy (Fig. 1). This one measures 65 × 25 × 40 cm and weights 25 kg. The printing area is 60 × 100 × 100 mm. The resolution on XY axes is ± 50 μm, while on Z axes goes from 5 to 100 μm. We choose a resolution of 10 μm. The material used is a photoresin (Share HT, product code: 9RE05HT. Produced by Sharebot).

The solid model is produced with a base and supports, which need to be removed afterwards (Fig. 2).

2.3. From the lab to the surgical table

Surgeons were asked to first establish a surgical plan on standard

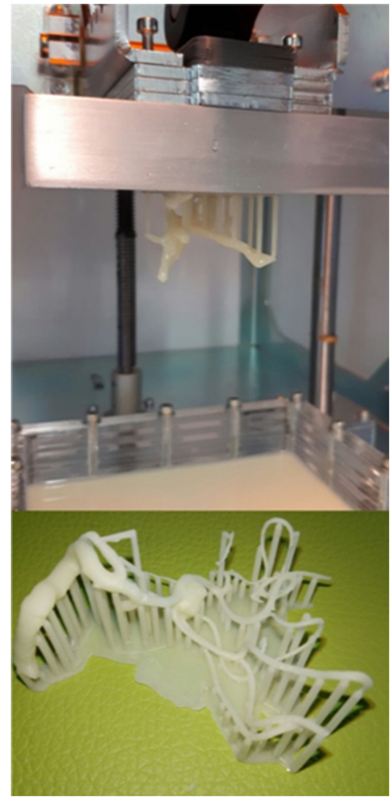

Fig. 2. The 3D model with base and supports.

DSAs or CTAs for each patient, in particular which kind of clip they were planning to use and if a single or multiple clipping. Afterwards, 3D models were presented and they were asked to perform the same evaluation of the type of clipping. The final surgical strategy was re-discussed also in the light of information acquired from the 3D aneurysm model. During the surgery, the sterilized models were available any times for further needing.

After the surgery, a survey about the usefulness of the 3D model by questionnaire was performed and the final type of clipping was recorded. We modified Ryan et al. [7] questionnaire (Supplemental materials) and ratings were provided on a five-point Likert scale.

Every patient underwent post-operative CTAs or DSAs in order to evaluate the parent vessels patency, the complete exclusion of the vascular malformation or the presence of a residual neck.

Patients and their family were asked the utility of the 3D models for the correct understanding of the disease.

3. Results

3.1. Demographic characteristics of the included patients

Table 1 reports patients and aneurysms characteristics.

3.2. Printing process, times and costs

The 5 biomodels produced from CTAs and DSAs replicated vasculature in a realistic fashion.

The biomodel of patient 1 was printed with the FDM technique. The STLs were created using Materialise® and post-processed using Blender®.

The remaining models were elaborated with 3DSlicer® and post processed using Slic3r®. They were printed with the ShareBot printer using a SLA technique.

Mean time to complete (mTc) the entire process with a manual .STL

Table 1
Aneurysms and clipping characteristics.

Patient	Aneurysm and dimensions	Estimate clip	Real clip	Residual neck
1	ACoA 4,5 mm	–	Straight	3 mm
2	Pericall 6 mm	Simple clipping	Simple clipping	None
3	ICA 3,7 mm MCA 3,4 mm M2 3,9 mm	Simple clipping	Simple clipping	None
4	ACoA 5 mm	Simple clipping	Simple clipping	None
5	MCA 6 mm	Multiple clipping	Multiple clipping	None

Table 2
Imaging and times for the 3D model printing. mTc: time for the completion of the entire process with manual STL creation; aTc time for the completion of the entire process with automatically STL creation.

Patient	Imaging	mT_c (min)	aT_c (min)
1	DSA	376	365
2	CTA	185	175
3	DSA	200	195
4	DSA	184	177
5	CTA	170	161
Mean values		223	215

creation was 223 min, while with an automatically .STL creation (aTc) was 215 min. Tc is the amount of the time for the .STL file elaboration (imaging review and selection of model segmentation that have been performed manually or automatically, the time of 3D printing and additional secondary time (time for pre-printing supports elaboration and post printing removal) (Table 2).

The mean cost for a 1:1 model was 1.23 euros.

The minimum thickness was 13 μm, which together with the thermic control technology allowed reaching an excellent definition. Vessels thinner than 1 mm were not replicated.

3.3. Clinical application

We asked 10 neurosurgeons to fill in the modified Ryan questionnaire score (see Supplemental materials). They appreciated the biomodels and reported that they accurately represent the intraoperative findings. They preferred the models printed by the SLA technique (patients 2, 3, 4, 5).

The complete overview of the anatomy from any perspective in a truly 3D way helped in the surgical planning. The size, configuration and orientation of the aneurysms and the relationship to the arterial branching pattern at the neck was clearly understood and found an accurate reflection of the intraoperative reality.

The model was found reliable, appropriate and superior to traditional images alone for the possible use as an educational tool for trainee surgeons and for explaining the disease and treatment to patients and relatives (informed consent) (see patient and family questionnaire scores on Supplemental materials).

3.4. Exemplificative cases

One of the biomodel was a control after an incomplete clipping (patient 1). It was evaluated with a critical attitude in order to understand if a better clipping was possible (Fig. 3a,b,c).

Patient 2 represented a very interesting case. He suffered from a subarachnoid hemorrhage caused by a ruptured left pericallosal artery firstly treated with coiling. Five years later a follow-up CTA showed a recurrence of the aneurysm (6 × 3 × 4 mm) (Fig. 4a,b,c). Surgery was planned and the 3D model was produced (Fig. 4d) showing the recurrence of the aneurysm and the previous placed coils. The patient underwent surgery (Fig. 4e) and the recurrence was clipped. A post-operative DSA showed a complete exclusion of the vascular malformation and the patient was discharged neurologically intact.

Patient 5 harbored a right MCA aneurysm with frontal and temporal M2 branches passing by very close to the neck and dome (Fig. 5a). The model was preoperatively studied positioning it in the intraoperative view and appreciating the exact 3D relationships between the aneurysm and the surrounding vessels (Fig. 5b). Because of these relationships, a multiple clipping was expected. The intraoperative view (Fig. 5c,d) was found very similar to the 3D model and a multiple clipping was performed.

4. Discussion

Additive manufacturing is a process in which successive layers of material are distributed to form 3D shapes. Tridimensional printing is transforming science and education. It is now being used to model complex molecules and protein interactions, and to fashion customized laboratory tools [8].

Applications within clinical medicine are emerging due to 3D printing's ability to produce individualized models, devices, and implants that can potentially improve patient care.

The field of neurosurgery, in particular, has experienced a broad interest in 3D printing [9]. With this technology, anatomical structures can be reconstructed from 3D volumes and produced as physical models. This presents very important implication both for surgical planning and simulations, providing a realistic representation of the surgical procedure without the risk of potential harm to a patient.

This application may enable surgeons to perform a personalized treatment to every patient.

In vascular neurosurgery, especially in aneurysm clipping procedures, surgeons need a complete and confident understanding of the positional relationship between the vascular malformation and the surrounding arteries, bones, brain, and cranial nerves. For this reason, stereolitography has been developed since 1999. D'Urso et al. [1] created the first 3D biomodels for complex intracranial aneurysms and arteriovenous malformations; thereafter, Wurm et al. [2,3] improved this technique by reproducing other variables such as the cranium and the cerebral vasculature. Many papers have been recently published, improving more and more the techniques and the accuracy. Most of them evaluate the usefulness for the simulation and training [4–7]; many authors used 3D printing for developing in vitro model of the biological effect of complex-flow stress on endothelial cells [10]; others focused their attention on hemodynamics on aneurysm growth, rupture, and treatment outcome [11,12].

Since 2017, we started experiences with 3D vascular models, and in this paper we presented the latest developments in creating a patient specific vascular 3D model with affordable costs and times.

4.1. Differences between our 3D models

The possibility to directly convert DICOM images in STLs together with their accuracy and production times measured in hours, allows anatomical models to potentially be delivered to clinicians “on-demand”.

We experienced 2 different software for the .STL elaboration.

The SLA printing technique (used to print all the biomodels except patient 1) was found to have a finer resolution, smooth and finished surfaces even if it is slower than FDM. Moreover SLA technique allows to use any kind of polymer including personalized “home-made” ones, while FDM usually uses precast polymers.

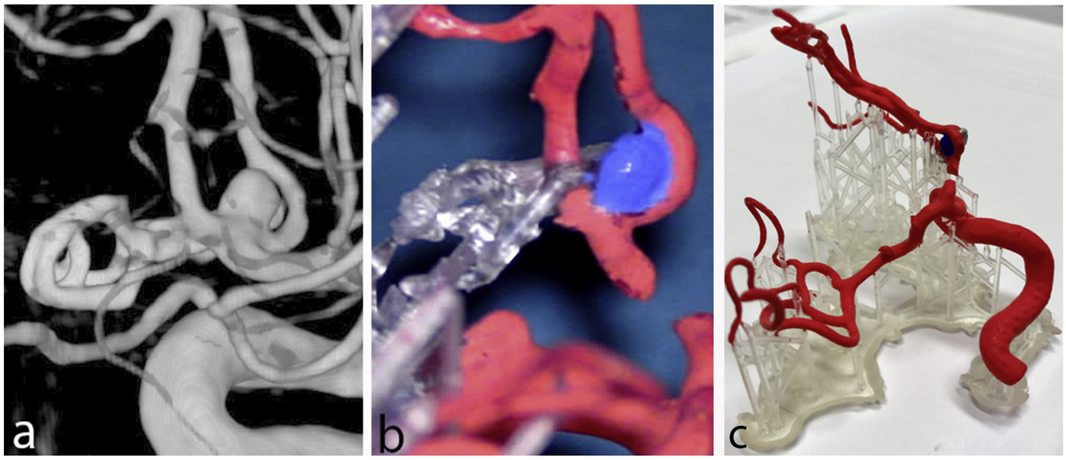

Fig. 3. Patient 1. a) Post operative DSA showing a residual of the aneurysm; b) detail of the 3D model showing the incomplete clipping. c) Overview of our first model printed with the FDM technique, showing the vascular tree and the partially clipped ACoA aneurysm of patient 1.

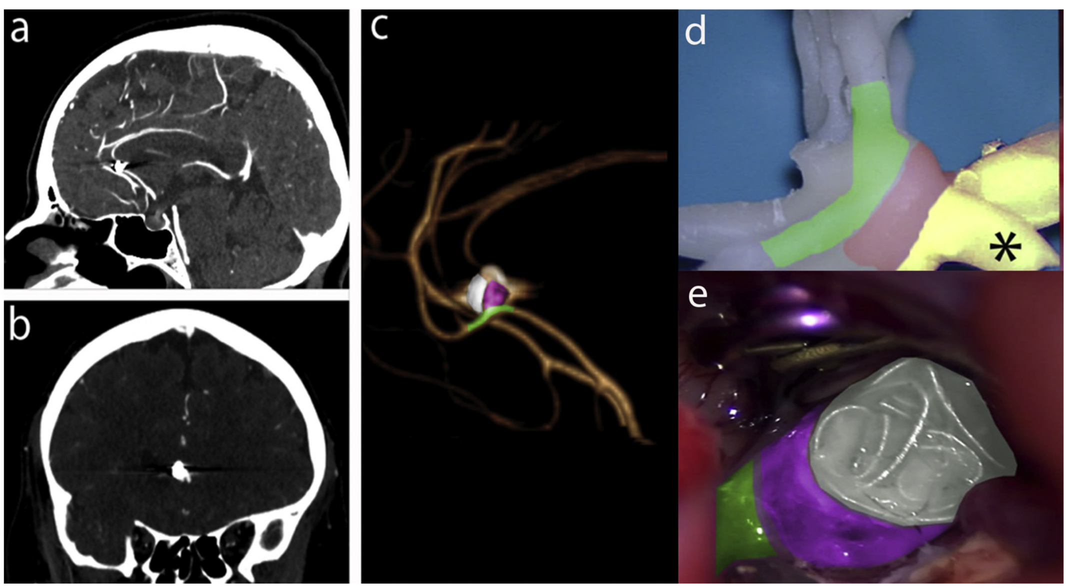

Fig. 4. Patient 2 CTA showing a recurrence of the left pericallosal artery aneurysm previously treated by coiling. a) Sagittal plane; b) coronal plane; c) 3D reconstruction from a lateral-lateral left view showing the coiled part (green), the residual part (pink) and the left pericalossal artery (green); d) 3D model showing the artifact of coils (*), the recurrence of the aneurysm (pink) and the pericallosal artery (light green); e) intraoperative view showing the coils (grey), the recurrence of the aneurysm (pink) and the pericallosal artery (light green). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Moreover, we found 3D slicer® a more suitable software for our purpose because it is certified for medical use, it is free and easier to use.

The quality of the preoperative DICOM files (CTA or DSA) is primary. We needed to adjust the imaging acquisition with established parameters, in order to guarantee a good quality of 3D printing.

Best models were reported to be the one developed from the DSA (patients 1, 3, 4). Thanks to the digital subtraction of bone signal and the absence of artifacts, the grey scale can be better defined and the software can reconstruct the model easily.

4.2. Conventional 3D images versus 3D solid models

Advanced imaging techniques, such as CT-angio or DSA guarantee realistic 3D models in a short time. However, a planar 3D image still remains a two-dimensional image created with a perspective technique. 3D models allow to acquire a multimodal information, coming from an optimal integration between signals acquired by different sensory modality (hand and eye) and, therefore, in fundamentally unrelated units.

4.3. The surgical planning

In complex cases, the creation of a 3D 1:1 replica of the patient's aneurysm may assist the surgeon in determining how to attack the aneurysm by selecting the best positioning and approach. Approaches may be modified to achieve better visualization and control of the lesion and to avoid potential damage to surrounding vessels. Types and number of clips as well as the way they should be applied for best results may be studied.

The survey showed a very high correspondence between the selection of the kind of clipping during the preoperative planning with the 3D model and the real clipping during the surgery (Table 1).

The reduced time of production (about 215 min) allows the 3D printing process to be proposed for patients presenting with ruptured aneurysms. In a Japanese study [13] the mean time from the

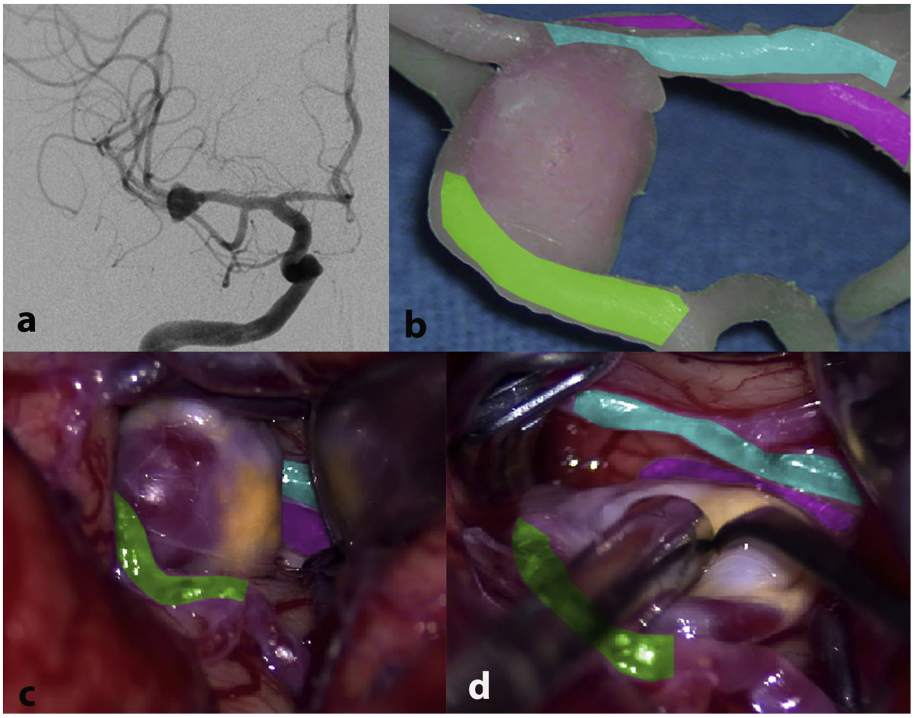

Fig. 5. Patient 5 harboring an MCA aneurysm. a) DSA showing a right MCA aneurysm. The frontal and temporal branches pass very close to the aneurysm dome and neck; b) 3D model showing M2 branch arising from the neck (pink) and the early M1 branch (light blue); c) intraoperative view showing the M2 frontal branch (light green) and 2 temporal branches (light blue and pink). The distinction between the M2 branch arising from the neck and the early M1 branch is not clear but the model matches the representation of all branches and helps in understanding better the anatomy; d) the vessels relationship with the neck of the aneurysm are clearly understood after the dome manipulation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

hospitalization to the start of the surgery is 242 min. Indeed, in our hospital the mean time between the CTA or DSA acquisition and the start of the craniotomy for a ruptured aneurysm is about 150 min. The model could be available for surgeons just before opening the Sylvian fissure allowing a better planning of the clipping, also in emergency surgery.

Patient 2 (coiled) and patient 1(clipped) show the feasibility and accuracy of stereolitography also in already treated cases.

4.4. The learning and training experience

Criticism of surgical training is increasing with concerns for the safety of patients undergoing any type of surgery, not only clipping. In addition, the development and wider use of endovascular treatment lowered the number of cerebral aneurysm clippings [14,15]. Research and training methods are essential for the safe surgical treatment of challenging pathologies such as vascular malformations. Simulation for surgical procedures has been tested and its advantages verified [16,17]. However, operative results of aneurysm clipping are highly depending on the capability to transfer the 2D image information into the actual surgical 3D field with immediate objective feedback of the performance. Simulations using physical models were developed by D'Urso et al. [1], Wurm et al. [2,3] and Kimura et al. [18].

We developed a method for simply fabricating inexpensive ABS cerebral arteries and aneurysms models and used them in pre-surgical simulation and surgical training.

4.5. Times and costs

Times and costs of the production were reduced in comparison to previous studies (Table 3).

The average cost for the models was about 1.23 euros. This is absolutely affordable allowing the stereolitography to be in the future fully integrated in the patient management and in the Neurosurgery learning and training programs. Unfortunately, the cost of the printer is still high (about 25.000 euros).

We also managed in achieve suitable times for 3D models production (Table 2). Indeed, the mean time resulted to be 223 min. In Table 2 we can see that the STL file creation can be automatically or manually performed. The automatic process is quicker, but sometimes results in a lower definition. In our experience, in DSAs elaboration there is almost no difference between manual or automatic elaboration; while CTAs usually need to be elaborated manually in order to obtain a better resolution of the model.

Table 3
Comparison of no. of models, time for printing and cost between the major published studies on 3D stereolitography.

Study	Year	No. of models	Time for printing	Cost
D'Urso et al. [1]	1999	16	3 days	268.3 E
Wurm et al. [3]	2011	–	1.5 weeks	2000 E
Namba et al. [20]	2015	10	12–24 h	1.25 E
Mashiko et al. [21]	2015	20	17.9 h	1.56 E
Mashiko et al. [19]	2016	3	3 days	178.8 E

Finally, we reproduced only the aneurysm with a small part of the vascular tree, while in other studies like the one by Wurm et al. [3] and Mashiko et al. [19] skull and brains were included in the models. We also didn't go for the process of obtaining hollow silicone casts (like Namba et al. [20] or Mashiko et al. [21]).

These factors could explain the longer times and higher costs reported in the other studies.

4.6. Limits

Models are made of a hard material that has a completely different consistency than the real vessels. Wurm et al. [3] and Mashiko et al. [19] developed a precise plastic replicas with hollowed out vessel sections, allowing serial clipping efforts, evaluation of different clips and clip positions really optimize the training of surgical skills. We still lack in this kind of complex representation. However, the cost of these models is higher and the time for the fabrication is longer if compared to ours.

We still did not manage in elaborating a protocol for image acquisition and sometimes experienced bad quality results in 3D models because of an incorrect DICOM files acquisition.

3D printing still presents few limitations if compared to conventional imaging 3D models. CTA or DSA are readily available in every hospital and image processing takes about 10 min. 3D printer are still quite expensive and are usually not supplied, especially in hospitals. They need specialist staff for the operating, maintenance and repair services for the machinery. The mean time to obtain a model is about 209 min, definitely longer than the conventional imaging. In addition, the mean cost of a 3D model is about 1.23 euros, while 3D imaging reconstructions are free.

The image threshold influences the visualization of vascular diameters.

Finally, (as reported by D'Urso et al. [1] and Mashiko et al. [19]) in case of a thrombosed aneurysms it's not possible to demonstrate and reconstruct the thrombus or the mural calcification.

4.7. What's next?

3D models more appropriate for training and simulation with affordable time and cost of production need to be developed. These models need to improve the consistency of the structures (vessels, brain parenchyma, arachnoid…) and vessels should be hollow (in order to be suitable also for endovascular training).

Complex aneurysms can be characterized by the presence of thrombi or calcification which often make the treatment challenging, especially when their relationship with the neck of the aneurysm cannot be clearly understood. Representation of these features in the 3D aneurysm models has to be developed.

5. Conclusions

The 3D printing process proposed for cerebral aneurysm models is time and cost efficient.

The models replicated patient-specific anatomy very precisely. Trained vascular neurosurgeons who pre-operatively used 3D models for the surgical planning, found them reliable and useful. Despite the potential, there still remains a notable lack of validation of 3D printing and steps taken to establish robust evidence are needed before widespread usage.

Acknowledgements

On behalf of all authors, the corresponding author states that:
Conflict of Interest: None.
Disclosure of Funding: None.
Ethical approval and informed consent were regularly collected.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.inat.2019.02.009.

References

[1] P.S. D'Urso, R.G. Thompson, R.L. Atkinson, M.J. Weidmann, M.J. Redmond, B.I. Hall, et al., Cerebrovascular biomodelling: a technical note, Surg. Neurol. 52 (1999) 490–500.
[2] G. Wurm, B. Tomancok, P. Pogady, K. Holl, J. Trenkler, Cerebrovascular stereolithographic biomodeling for aneurysm surgery. Technical note, J. Neurosurg. 100 (2004) 139–145.
[3] G. Wurm, M. Lehner, B. Tomancok, R. Kleiser, K. Nussbaumer, Cerebrovascular biomodeling for aneurysm surgery: simulation-based training by means of rapid prototyping technologies, Surg. Innov. 18 (2011) 294–306.
[4] J.L. Wang, Z.G. Yuan, G.L. Qian, W.Q. Bao, G.L. Jin, 3D printing of intracranial aneurysm based on intracranial digital subtraction angiography and its clinical application, Medicine (Baltimore) 97 (2018) e11103.
[5] L. Wang, X. Ye, Q. Hao, L. Ma, X. Chen, H. Wang, et al., Three-dimensional intracranial middle cerebral artery aneurysm models for aneurysm surgery and training, J. Clin. Neurosci. 50 (2018) 77–82.
[6] Y. Liu, Q. Gao, S. Du, Z. Chen, J. Fu, B. Chen, et al., Fabrication of cerebral aneurysm simulator with a desktop 3D printer, Sci. Rep. 7 (2017) 44301.
[7] J.R. Ryan, K.K. Almefty, P. Nakaji, D.H. Frakes, Cerebral aneurysm clipping surgery simulation using patient-specific 3D printing and silicone casting, World Neurosurg. 88 (2016) 175–181.
[8] S.V. Murphy, A. Atala, 3D bioprinting of tissues and organs, Nat. Biotechnol. 32 (2014) 773–785.
[9] M. Randazzo, J.M. Pisapia, N. Singh, J.P. Thawani, 3D printing in neurosurgery: a systematic review, Surg. Neurol. Int. 7 (2016) S801–S809.
[10] N. Kaneko, T. Mashiko, K. Namba, S. Tateshima, E. Watanabe, K. Kawai, A patient-specific intracranial aneurysm model with endothelial lining: a novel in vitro approach to bridge the gap between biology and flow dynamics, J. Neurointerv. Surg. 10 (2018) 306–309.
[11] M.R. Levitt, M.C. Barbour, S. Rolland du Roscoat, C. Geindreau, V.K. Chivukula, P.M. McGah, et al., Computational fluid dynamics of cerebral aneurysm coiling using high-resolution and high-energy synchrotron X-ray microtomography: comparison with the homogeneous porous medium approach, J. Neurointerv. Surg. 9 (2017) 0,2016–012479 (Epub 2016 Jul 12).
[12] J.R. Anderson, R. Klucznik, O. Diaz, Y.J. Zhang, G.W. Britz, R.G. Grossman, et al., Quantification of velocity reduction after flow diverter placement in intracranial aneurysm: an ex vivo study with 3D printed replicas, Conf. Proc. IEEE Eng. Med. Biol. Soc. 2015 (2015) 7300–7303.
[13] T. Konno, T. Mashiko, H. Oguma, N. Kaneko, K. Otani, E. Watanabe, Rapid 3-dimensional models of cerebral aneurysm for emergency surgical clipping, No Shinkei Geka 44 (2016) 651–660.
[14] M.T. Lawton, R. Du, Effect of the neurosurgeon's surgical experience on outcomes from intraoperative aneurysmal rupture, Neurosurgery 57 (2005) 9,15 (discussion 9-15).
[15] N. Sanai, N. Caldwell, D.J. Englot, M.T. Lawton, Advanced technical skills are required for microsurgical clipping of posterior communicating artery aneurysms in the endovascular era, Neurosurgery 71 (2012) 285–294 (discussion 294-5).
[16] C. Grifasi, A. Calogero, A. Esposito, C. Dodaro, Perioperative care of elderly outpatients. A review, Ann. Ital. Chir. 86 (2015) 100–105.
[17] T.P. Grantcharov, V.B. Kristiansen, J. Bendix, L. Bardram, J. Rosenberg, P. Funch-Jensen, Randomized clinical trial of virtual reality simulation for laparoscopic skills training, Br. J. Surg. 91 (2004) 146–150.
[18] T. Kimura, A. Morita, K. Nishimura, H. Aiyama, H. Itoh, S. Fukaya, et al., Simulation of and training for cerebral aneurysm clipping with 3-dimensional models, Neurosurgery 65 (2009) 719–725 (discussion 725-6).
[19] T. Mashiko, N. Kaneko, T. Konno, K. Otani, R. Nagayama, E. Watanabe, Training in cerebral aneurysm clipping using self-made 3-dimensional models, J. Surg. Educ. 74 (4) (2017) 681–689, https://doi.org/10.1016/j.jsurg.2016.12.010 [Epub 2017 Jan 16].
[20] K. Namba, A. Higaki, N. Kaneko, T. Mashiko, S. Nemoto, E. Watanabe, Microcatheter shaping for intracranial aneurysm coiling using the 3-dimensional printing rapid prototyping technology: preliminary result in the first 10 consecutive cases, World Neurosurg. 84 (2015) 178–186.
[21] T. Mashiko, K. Otani, R. Kawano, T. Konno, N. Kaneko, Y. Ito, et al., Development of three-dimensional hollow elastic model for cerebral aneurysm clipping simulation enabling rapid and low cost prototyping, World Neurosurg. 83 (2015) 351–361.