Point-of-Care 3D Printing: a Low-Cost Approach to Teaching Carotid Artery Stenting

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Point-of-Care 3D Printing: a Low-Cost Approach to Teaching Carotid Artery Stenting

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ABSTRACT

Background

Carotid Artery Stenting (CAS) is increasingly being used in selected patients as a minimal invasive approach to carotid endarterectomy. Despite the abundance of performed endovascular treatments, the concept of stent-placement is still unclear to many patients. Furthermore, visual feedback on stent-deployment is difficult to obtain as it is always performed under radiographic feedback. Three-Dimensional (3D) printing might tackle both challenges. A particular use case of Point-of-Care 3D Printing is the pretreatment printing of vascular anatomy in support of endovascular procedures.

Purpose

This study reports the first use of a low-cost patient-specific 3D printed model for CAS education to both experienced surgeons and patients.

Methodology

An angio computed tomography (CT) scan was segmented and converted to STL format using Mimics inPrint™ software. The carotid arteries were bilaterally truncated to fit the whole model on a Formlabs 2 printer without omitting the internal vessel diameter. Next, this model was offset using a 1 mm margin. A ridge was modelled on the original vessel anatomy which was subsequently subtracted from the offset model in order to obtain a deroofed 3D model. All vessels were truncated as to facilitate flow on the inside.

Results

Date-expired carotid artery stents were successfully deployed inside the vessel. The deroofing allows for clear visualization of the bottlenecks and characteristics of CAS deployment and positioning, including foreshortening and tapering of the stent. This low-cost 3D model provides insights in stent deployment and positioning, and allows for patient-specific procedure planning.

Conclusion

Printing patient-specific 3D models preoperatively could assist in accurate patient selection, a better preoperative planning and case-specific training. Furthermore, this 3D model also allows for better patient education and informed consent. However, more research is warranted to evaluate the added value of these models.

Keywords

Carotid Artery Stenting, 3D Printing, Training, Surgical Education, Informed Consent, Phantom

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INTRODUCTION

Background

Carotid artery stenosis affects 10% of the population by the age of 80 and is associated with an increased risk of cerebrovascular events with major consequences on physical and neurological level.[1,2,3] Worldwide, carotid revascularization is advised for stroke prevention and can be obtained by carotid endarterectomy (CEA) or Carotid Artery Stenting (CAS).[4,5] Until recently, CEA, i.e. removal of the atherosclerotic plaque via a neck incision, has been the golden standard.[1,6,7,8] The introduction of endovascular techniques, e.g. balloon angioplasty and stenting procedures, demarked a shift towards the less invasive approach of CAS.[6,7] The major risk of both procedures is periprocedural stroke with a slightly higher risk upon CAS compared to CEA.[1,5,7] On the other hand, CAS was associated with a slightly lower risk for periprocedural myocardial infarction compared to CEA.[5] In general, today's surgery focuses more on minimal invasive techniques because of its advantages including a shorter recovery period, decreased postoperative pain and discomfort, smaller incisions and shorter length of hospital stay.[6,8] Particularly for CAS, a shorter recovery period and less procedural discomfort is observed as well as enhanced physical function in the first post-operative year.[6,9] To optimize fast recovery and mitigate the slightly higher risk for periprocedural stroke upon CAS, it is imperative to optimize these endovascular techniques. Moreover, minor errors can have disastrous consequences such as carotid artery dissection and distal embolization, and thus potentially increase the risk of stroke.[4,5,6,8] Proper patient selection, pre-operative planning and training can help mitigate these risks.[7] In addition, the hospital and surgeon CAS volume is a major determining factor in the patient outcome.[7,10]

Overall, no clear guidelines are available for the use of CEA and CAS.[2,7] To date, CAS is an alternative to CEA in selected cases, and it is preferred over CEA in specific indications including prior radiotherapy, prior neck dissection, contralateral laryngeal nerve damage, contralateral carotid occlusion, re-stenosis after CEA and patients with high risk for surgery.[2,3,5,6,8]

Patient selection and preoperative planning

Nowadays, surgery is based on radiologic imaging such as angio-CT, which frequently fails to give detailed information on the exact vascular structure of the patient, e.g. due to limited imaging resolution.[11] Moreover, everyone's anatomy is unique, and the occurrence of anatomical variants and abnormalities of the carotid artery is widely observed.[11] Ideally, a patient-specific 3D model could extend the patient selection and the pre-operative planning by enhancing the practitioner's understanding of the patient-specific 3D anatomy. All together, these factors can contribute to a better approach and prevention of errors.[12,13] Various surgical societies provide different guidelines on CAS[2,5,7], which might indicate a growing need for standardization or further point toward a need for case-specific simulation.

Due to the technical nature of CAS, patients lacking a medical background often do not entirely comprehend the procedure they will undergo and the risks that are involved.[11] Informing the patient based on his/her 3D model instead of two-dimensional (2D) imaging, as well as the switch from visual to visual and tactile information will lead to better patient education and enhance informed consent.[11, 12]

Training of CAS

Performing CAS requires training and expertise.[4,6] Little training and poor technical skills lead to higher procedure-related complication rates, fluoroscopic time, contrast volume and longer operation time.[1,6] Hence, besides being fully credential in peripheral endovascular techniques and already performing various catheter procedures, the hands-on training of these practitioners is necessary to enhance clinical proficiency for this specific endovascular procedure.[1,4,6] Nowadays, training is based on endovascular simulation modules and industry-sponsored courses,[1,4,6,7] which can provide a shortened learning curve and may limit complications.[1,7] Adding case-specific virtual reality (VR) simulation to these training sessions could hone technical skills, especially for difficult and more rare cases.[7,13,14] Printing a patient-specific 3D model preoperatively enables to train this specific case and could therefore contribute to a straightforward approach with less catheter manipulation, shorter procedure time, a more confident surgeon and thus overall improvement of the procedure.

3D models

The installation of a 3D Printing service in a medical center is being increasingly implemented globally. Driven by the increasing performance of desktop 3D printers and accompanying lower production costs, shorter time-to-product and easy-to-use 3D editing programs, more hospitals start to insource 3D Printing. A particular use case of this so-called Point-Of-Care printing is the pretreatment printing of vascular anatomy in support of endovascular procedures.

Purpose

Many articles describe the importance of accurate patient selection, preoperative planning and the key aspects of training in CAS procedure for the patient's outcome. Preoperative printing of patient-specific 3D models could enhance patient selection, extend the preoperative planning and provide preoperative rehearsal of the specific case and the often challenging anatomy in general.
In this paper, we present a cost-effective workflow to perform CAS on a patient-specific 3D model.

METHODOLOGY

We present the case of an 80 year old male with severe stenosis at the level of the right internal carotid artery (Figure 1). The pre-operative angio-CT scan was segmented and converted to a 3D printable .STL format using Mimics inPrint 3.0 software (Materialise, Leuven, Belgium). In order to print the model with correct internal vessel diameters in one single build but to keep the aortic arch in place for realistic simulation, we chose to bilaterally shorten the common carotid arteries (from Figure 2.A. to 2.B.), and apply a vessel wall thickness of 1mm. To facilitate stent deployment view in the translucent material, we chose to deroof a viewing window at the level of the carotid bifurcation. This was achieved by modelling a ridge on the original vessel anatomy (Figure 2.C.), which was subsequently subtracted from the 1 mm offset model resulting in our final model (Figure 2.D.). Deroofing allowed for better visual feedback without requiring extra manual post-processing such as sanding or application of coatings which are frequently used to improve translucency after printing.
Truncation, fusion and ridge editing were performed in Meshmixer (Autodesk, California, USA), without omitting the internal vessel diameter. All arterial ends were left open to facilitate internal flow.
The model was printed in one single run on a desktop Formlabs 2 printer (Formlabs, Somerville, Massachusetts, USA) with build volume 145 × 145 × 175 mm (Figure 3). Total printing time was 9h45min with a total volume of 61.48 ml.

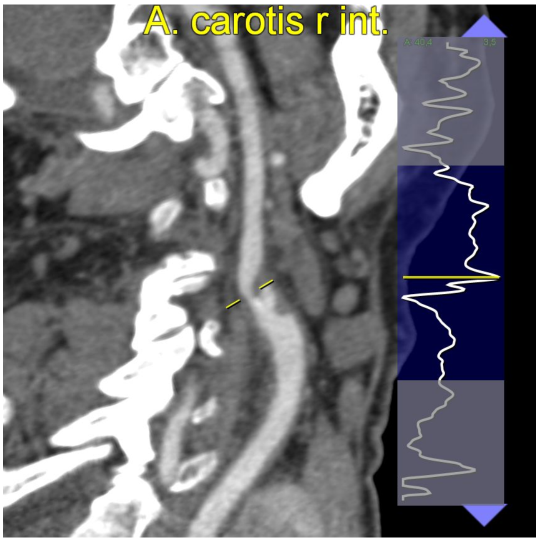

Figure 1: Cross-sectional sagittal carotid view
Severe carotid artery stenosis at the level of the right internal carotid artery, as indicated by the yellow line.

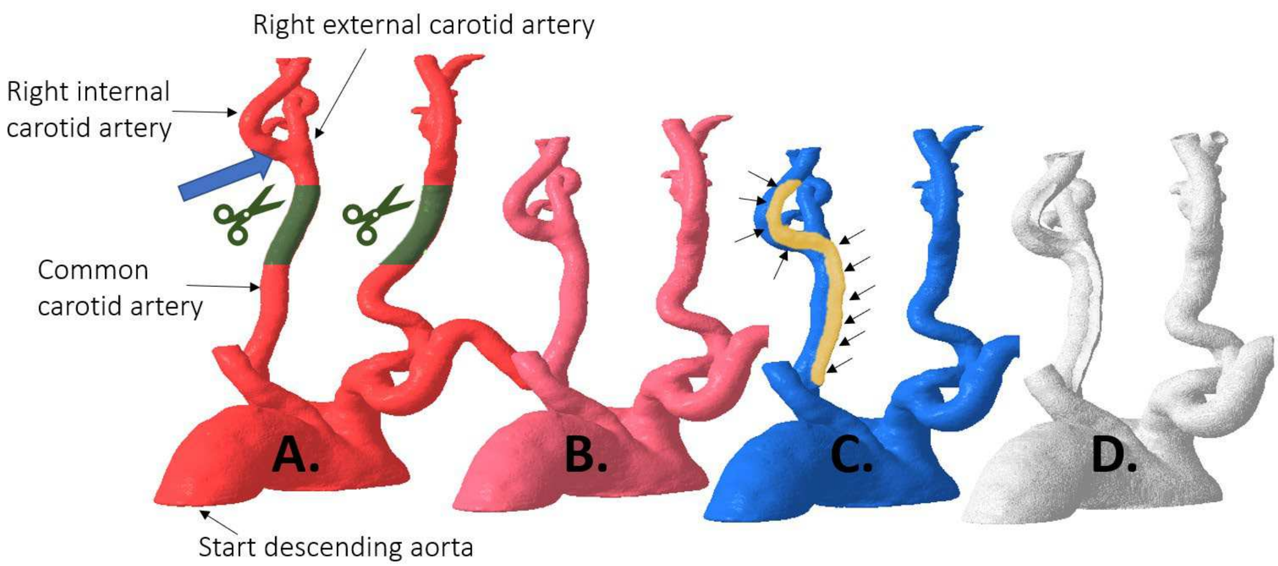

Figure 2: Posterior view of the aortic arch with subsequent editing steps to obtain the final model

A. In red, the anatomy is depicted as derived from the angio-CT. The part in green is cut out to truncate the model to fit within the building volume of the printer. The blue arrow indicates the stenosis location.
B. The pink model is the result of the truncation at the common carotid artery level.
C. The blue model shows the manually added and gold colored ridge, also indicated by the arrows.
D. The white model shows the final model, which is the result of offsetting the pink model B by 1 mm and subtracting the blue model C. The white model is printed as depicted in Figure 3.

Figure 3: 3D Print
The 3D-printed model, with apparent translucency. Catheter Sheat is already in place within the right internal carotid artery, ready for stent deployment.

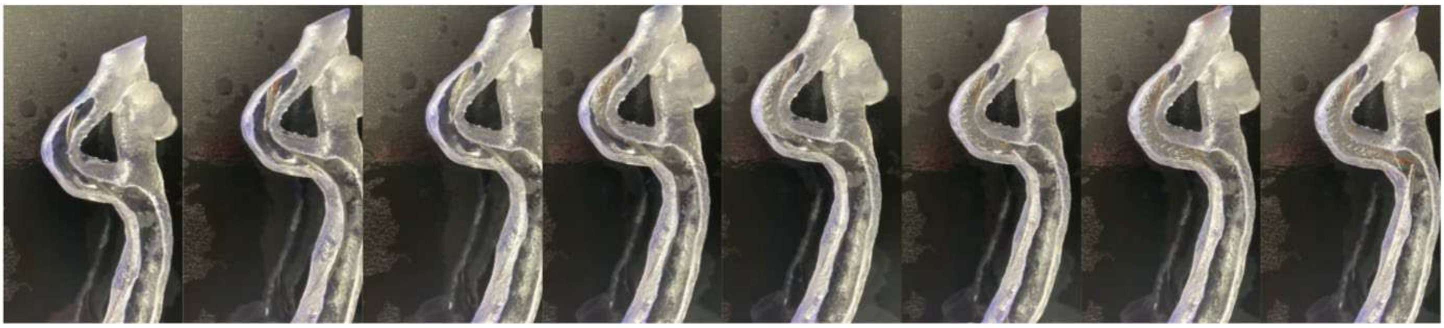

Figure 4: Stent deployment
Deroofed model allows for precise vision of the deployment, a feature which is not appreciable in completely closed translucent models.

RESULTS

Date-expired 5 Fr Nitinol dual layer CAS stents were successfully deployed inside the model. This type of stent can shorten up to 2/3 in length during deployment, which is crucial for correct positioning. Deroofing allows for precise visual feedback of this important feature during CAS implantation (Figure 4). Release of the proximal stent end with accompanying recoil can also readily be objectivated (videolink attached). Hence, this model provides unseen insights in stent positioning and allows for patient-specific procedure planning. Furthermore, it also enables better patient-education and improves informed consent. Comparison with post-procedure in-patient imaging was not possible due to poor renal function. As such, contrast enhanced follow-up imaging was avoided and patency was assessed using duplex ultrasound only.

DISCUSSION

We demonstrated a low-cost approach to teaching CAS, which is an accepted alternative to carotid endarterectomy for revascularization in patients with carotid bifurcation disease.[4,5,6] A 3D printed model of the patient's vascular anatomy including the detailed bifurcation disease could contribute to a proper risk factor analysis and to the prevention of complications. Towards the future, it may be possible to extend the indications for CAS through refined preoperative planning and training based on patient-specific 3D models, e.g. to overcome relative contra-indications such as carotid tortuosity.[6] 3D models might enable training by allowing testing on difficult anatomical variations which cannot be observed in animal models. In addition, Gosling et al indicated that including simulation courses in the training of CAS procedures could shorten the learning curve, especially for more rare patient cases, and lead to better patient outcomes.[1] Also, preoperative rehearsal of selected cases through patient-specific 3D printed models might improve clinical outcome, and in-hospital 3D-printing services can facilitate this movement. Deroofing of the model and accompanying editing steps, might be omitted by manual sanding and coating of the model after printing to obtain a transparent instead of translucent model. However, complete transparency might be hard to reach in UV cured polymers. Moreover, they tend to yellow out when exposed to daylight too long. Both modeling of the ridge and post-processing through sanding/coating require time. The main advantage of implementing a viewing window by means of adding a virtual ridge is that the use of a special setup with creation of sanding dust and release of hazardous chemicals by coating is avoided, both of which we believe are equally important in a point-of-care setting.
One major drawback of our model is its rigidity, hence no tissue deformation and manipulation can occur. Future tests should involve printing of the newly developed elastic resins and the investigation of model deformation. Another major drawback of this proof-of-concept is the lack of comparison to post-operative imaging. This should also be addressed in future research.

CONCLUSION

CAS has a very specific learning curve and currently, no 3D printed models exist to explain the pitfalls during this procedure. Preoperative patient-specific 3D printed models might enhance the patient's outcome through assisting in accurate patient selection, better preoperative planning, case-specific training and thorough informed consent. Here, we present a framework to generate patient-specific 3D models in the point-of-care setting, which should allow for easier adaptation and implementation. However, more research is warranted to evaluate the value of these models.

LIST OF ABBREVIATIONS

STL	Standard Tessellation Language
CAS	Carotid artery stenting
CEA	Carotid endarterectomy
CT	Computed tomography
2D	Two-dimensional
3D	Three-dimensional

DECLARATIONS

Ethics approval and consent to participate

Ethics approval by hospital ethics committee reference 2020/140.

Consent for publication

Not applicable

Availability of data and materials

Video-fragment available:
https://drive.google.com/file/d/12bXLJJeazWQ8JsAhJCb8BQQAOmJQ4RUO/view?usp=sharing

Competing interests

The authors declare that they have no competing interests

Funding

None

Authors' contributions

PDB designed the 3D model, performed the printing and wrote the manuscript together with CA. CD supervised writing. RB provided the clinical case, deployed the stent inside the model as part of an endovascular course and supervised the writing of the manuscript. All authors read and approved the final manuscript.

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Authors' information

PDB is a 3th year urology resident with a master's degree in biomedical engineering. CA is a 4th year medical student at Ghent University with a master degree in physiotherapy. CD is a professor in biomedical engineering (numerical biomechanics) at Ghent University. RB is a thoraco-vascular surgeon at OLV Hospitals.

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Figures

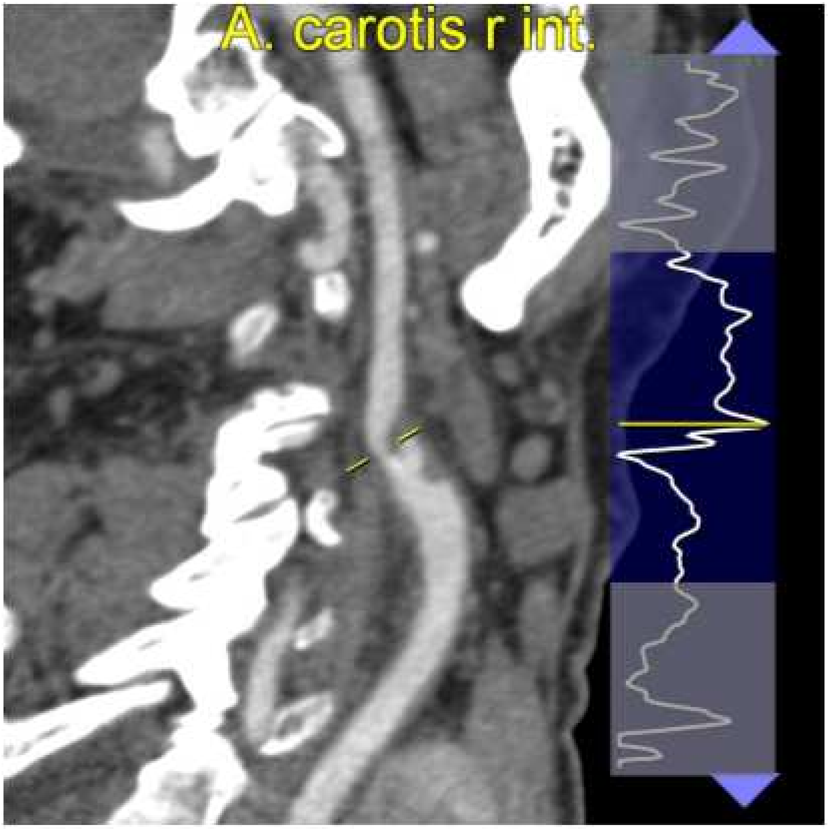

Figure 1

Cross-sectional sagittal carotid view Severe carotid artery stenosis at the level of the right internal carotid artery, as indicated by the yellow line.

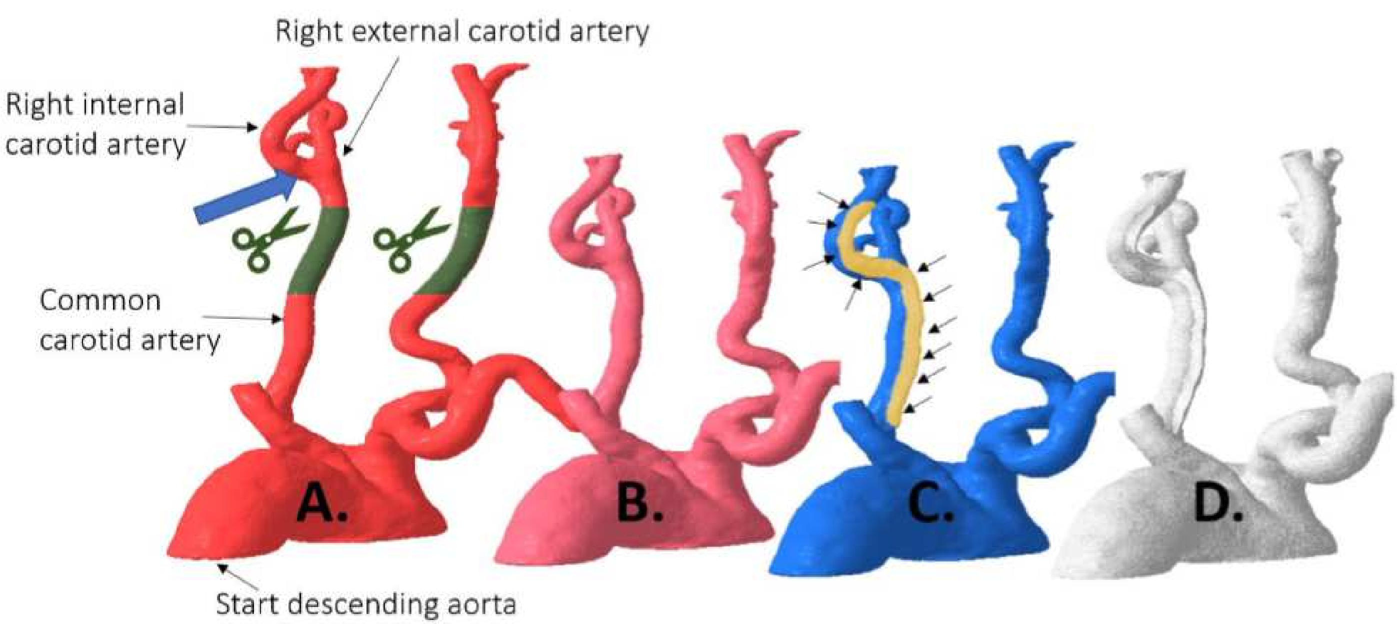

Figure 2

Posterior view of the aortic arch with subsequent editing steps to obtain the final model A. In red, the anatomy is depicted as derived from the angio-CT. The part in green is cut out to truncate the model to fit within the building volume of the printer. The blue arrow indicates the stenosis location. B. The pink model is the result of the truncation at the common carotid artery level. C. The blue model shows the manually added and gold colored ridge, also indicated by the arrows. D. The white model shows the final model, which is the result of offsetting the pink model B by 1 mm and subtracting the blue model C. The white model is printed as depicted in Figure 3.

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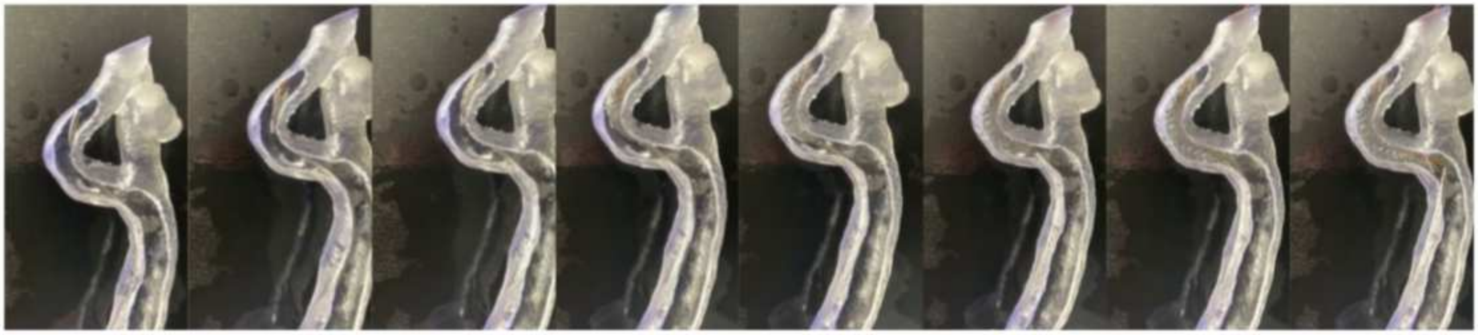

Figure 4

Stent deployment Deroofed model allows for precise vision of the deployment, a feature which is not appreciable in completely closed translucent models.