Three-Dimensional Printing for Perioperative Planning of Complex Aortic Arch Surgery

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Purpose. In this study, we show the use of three-dimensional printing models for preoperative planning of surgery for patients with complex aortic arch anomalies.

Description. A 70-year-old man with an extensively arteriosclerotic aneurysm reaching from the ascending aorta to the descending aorta was referred to our center for complete aortic arch replacement. We visualized and reconstructed computed tomography data of the patient and fabricated a flexible three-dimensional model of the aortic arch including the aneurysm.

Evaluation. This model was very helpful for the preoperative decision making and planning of the frozen elephant trunk procedure owing to the exact and lifelike illustration of the native aortic arch.

Conclusions. Three-dimensional models are helpful in preoperative planning and postoperative evaluation of frozen elephant trunk procedures in patients with complex aortic anatomy.

Surgery of aortic arches with complex anatomy, eg, extensive thoracic aortic aneurysms or aortic dissections, remains a challenge in cardiac surgery. The frozen elephant trunk (FET) procedure is a surgical technique developed for patients with aortic diseases involving the arch as well as the thoracic descending aorta [1, 2]. It allows single-stage treatment for such disease, combining conventional surgery with endovascular techniques. Preoperative planning and simulation of the procedure is often difficult because of the unpredictable anatomy of the aortic arch [3]. Therefore it might be of great value to develop high-quality preoperative data for optimal surgical planning and simulation of an FET procedure.

We developed a new rapid-prototyping technique to build three-dimensional models of the exact anatomy of the aortic arch in patients with complex aortic anatomy planned for an FET procedure. Rapid prototyping (stereolithography) is a technique used in engineering for building prototype models. Transferring this technology to cardiac surgery enables illustrating the exact anatomy of complex cardiovascular diseases for preoperative planning and decision making, hands-on simulation of the procedure, and intraoperative orientation.

Technology and Technique

We present the case of a 70-year-old man with an extensive arteriosclerotic aneurysm reaching from the ascending aorta to the descending aorta. The patient’s comorbidities included arterial hypertension and diabetes mellitus. The patient was referred to our institution for complete aortic arch replacement. We performed a 64-slice computed tomography (CT) of the patient’s chest, visualizing the aneurysm that measured 5.5 cm in width. Owing to the complexity of the aortic anatomy and the severe calcifications of the aneurysm and the aortic arch, we decided to build a three-dimensional (3-D) model for better decision making and preoperative planning of an FET procedure (Fig 1).

The patient’s CT dataset was loaded into an image processing and visualization software (Amira, Visualization Sciences Group, Burlington, MA), with which extraction of the aorta was completed in several steps. The user provided a seed position within the aorta to initiate a region growing with connected thresholds criteria. The lower intensity threshold was defined as 200 Hounsfield units (HU), and the upper intensity threshold was defined as 600 HU. Any pixel intensity within these thresholds was labeled as being part of the aorta. Manual segmentation corrections were performed to eliminate leaking voxels from the region growing. Erosion and dilation morphologic operators were subsequently applied to create the wall of the aorta with a wall thickness of 2 to 3 mm. Calcified depositions were similarly segmented.
Clinical Experience

The replica allowed us to better understand the disease of the aortic arch by holding the model in our hands and inspecting it from all angles.

Furthermore, we were able to talk ourselves through the procedure on a lifelike model, facilitating the intraoperative decision concerning the length and depth of the stent graft implantation and the landing zone. If needed, the procedure can also be simulated practically because the models are fabricated in a hollow fashion. However, this was not absolutely necessary in our case because the aortic anatomy was well illustrated through the model. The FET procedure was performed without problems (Figs 2, 3). We used a 23-mm Perimount aortic valve (Edwards Lifesciences, Irvine, CA), a 32-mm Tetrabranch arch prosthesis (Jotech GmbH, Hechingen, Germany), and a 36-mm Evita open descendens-hybrid (Jotech GmbH). The postoperative course was uneventful. At 12 months’ follow-up, the patient is doing well.

Fig 1. Three-dimensional model of the native aorta including the aneurysm. The “+” indicates the ascending aorta, the “*” indicate the supraaortic vessels. The arrows show the aneurysm reaching from the ascending to the descending aorta.

Fig 2. Intraoperative view on the operative field at the beginning of the operation. The “+” indicates the ascending aorta, the “*” indicate the supraaortic vessels. The arrows (black and white) show the aneurysm reaching from the ascending to the descending aorta.

using region growing with connected threshold criteria. Thus, any pixel intensity higher than 600 HU was labeled as being part of a calcified deposition. Final manual segmentation corrections were performed to eliminate irrelevant artifacts.

Finally, a virtual 3-D surface model of the aorta was created from the segmentation mask (Fig 1). Physical models of the resulting virtual 3-D surface models were created by a 3-D printer (Spectrum Z 510, ZCorporation, Rock Hill, SC). After completion of printing, the model was infiltrated using elastomeric urethane resin (Por-A-Mold 2030). The resulting structure was flexible, tough, and having a rubberlike quality. It is therefore possible to sew the model if you wanted to simulate the ascending aorta part of the procedure. The preoperative model demonstrates the exact anatomy of the aortic root including valve, leaflets, coronary arteries, ascending aorta, aortic arch, brachiocephalic artery, carotid arteries, subclavian arteries, and descending aorta (Fig 1).
A postoperative model of the aorta using postoperative images was built using the same approach with the additional identification of the stent (Fig 4). The postoperative model is tricolored, showing the native aorta in red, the prosthesis in white, and the stent material in brown.

Comment

Stereolithography has been demonstrated to be useful in different medical fields [4]. Since a couple of years ago, this technology is also used in adult and pediatric cardiac surgery [5–8]. The lifelike, 3-D models allow simulating different procedures and reconstructing required anatomic structures before surgery. There is a huge variety of clinical situations in which stereolithographic models might be helpful for perioperative planning.

Surgery of complex aortic arch diseases is still a challenge in cardiac surgery as a result of the often unpredictable anatomy. We present a patient with a calcified, extended aneurysm from the ascending to the descending aorta. This pathologic process can be treated in one single operation using the FET procedure provided that there is a suitable landing zone in the descending aorta [1]. However, in degenerative aneurysms, the depth and diameter of the landing zone are essential information for the selection of the stent graft [2]. In particular, the surgeon should ensure that the stent graft is long enough to reach the desired landing zone. Especially in huge aneurysms, this preoperative planning is often difficult despite modern imaging techniques such as CT.

Sulaiman and associates [9] fabricated a stereolithographic model of an aortic arch, using data of a patient with an aneurysm of the proximal descending aorta, to simulate stenting of the aneurysm on the model. Nevertheless, the authors did not describe how they treated the patient afterward and how useful the model was in doing so. Furthermore, a postinterventional model was not fabricated to evaluate the result of the procedure.

In our patient the aortic measuring variables obtained through the CT scan data and the 3-D model did not differ. However, in degenerative aneurysms, the depth and diameter of the landing zone are essential information for the selection of the stent graft [2]. In particular, the surgeon should ensure that the stent graft is long enough to reach the desired landing zone. Especially in huge aneurysms, this preoperative planning is often difficult despite modern imaging techniques such as CT.

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zone in our patient, even if the same measuring variables were obtained through the CT scan.

Furthermore, a stereolithographic model might allow the surgeon to anticipate pitfalls and problems concerning the high-risk operation on the individual aortic arch with complex anatomy. An additional postinterventional 3-D model of the aortic arch was fabricated to exactly visualize the surgical result.

Not every patient undergoing aortic arch surgery is a candidate for fabrication of stereolithographic models. The procedure has to be planned electively, because the fabrication of the models takes longer than 24 hours. The material costs for a model in this case were approximately $660 (490 euro). We think that especially in patients who require tailored surgical approaches owing to complex aortic disease processes and other comorbidities, stereolithographic models for perioperative planning might be superior to other imaging data. Our patient was already 70 years old with certain comorbidities such as diabetes mellitus and hypertension. It was our aim to choose an individual therapy for our patient with a minimum of risk and a good quality of life postoperatively.

Stereolithography is currently not established in cardiac surgery. However, we successfully used this technology in complex cases for preoperative planning, simulation of procedures, intraoperative orientation, and postoperative evaluation of the result. Furthermore, these models allow precise explanation of the procedure to patients, colleagues, and students.

To our knowledge, this is the first report on the use of stereolithography in patients with complex aortic arch anatomy planned for an FET procedure. Future studies including more patients are expected to show that stereolithography facilitates preoperative planning and decreases the risk of complex aortic arch surgery.

Disclosures and Freedom of Investigation

We had no funding source for this study. This study was conducted with freedom of investigation.

References


Disclaimer

The Society of Thoracic Surgeons, the Southern Thoracic Surgical Association, and The Annals of Thoracic Surgery neither endorse nor discourage use of the new technology described in this article.

INVITED COMMENTARY

The use of rapid-prototyping (stereolithography) for three-dimensional (3D) modeling is being applied more frequently in engineering and industry. Although its use has been reported sporadically in medicine for more than two decades, the role of rapid-prototyping (3D printing) in cardiovascular surgery has yet to be defined [1].

Concerned by the complex anatomy and calcifications in the transverse arch, the authors of the current report constructed a prototype of the patient’s involved thoracic aortic segment using a 3D printer from high-definition computed tomographic scan data [2]. From this prototype, image data were processed, allowing extraction of the aorta with differentiation of the calcium from aortic wall, rendering a 3D aortic model. This data were then entered into the 3D printer, and a surface model was created that was then lined with a urethane resin, ultimately creating an exact model of the patient’s thoracic aorta. According to the authors [2], this replica was then used to “better understand the pathology of the aortic arch,” and allow for better preoperative planning as it applied to the placement of the frozen elephant trunk distally in the descending thoracic aorta.

For any procedure performed, preoperative planning is essential, and visual 3D rendering using CT angiography is often more than adequate. On a daily basis, surgeons visually recreate the surgical area of interest never having the opportunity to manipulate a 3D replica before surgery. In the current report, the use of 3D printing to create an actual replica of the thoracic aorta was fascinating but likely superfluous.