Case Report

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A 3-Dimensional Printed Aortic Arch Template to Facilitate the Creation of Physician-Modified Stent-Grafts

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Abstract

Purpose: To demonstrate the utility of a 3-dimensional (3D) printed template of the aortic arch in the construction of a fenestrated and scalloped physician-modified stent-graft (PMSG). **Case Report:** A 73-year-old woman with descending thoracic aneurysm was scheduled for thoracic endovascular aortic repair after being disqualified for open surgery. Computed tomography angiography (CTA) revealed no proximal landing zone as the aneurysm began from the level of the left subclavian artery, so a fenestrated/scalloped PMSG was planned. To facilitate accurate placement of the openings in the graft, a 3D printed aortic arch template was prepared from the CTA data and gas sterilized. In the operating room, a Valiant stent-graft was inserted into the 3D printed template and deployed. Using ophthalmic cautery, a fenestration and a scallop were created; radiopaque markers were added. The PMSG was successfully deployed with no discrepancy between the openings and the target vessels. **Conclusion:** A 3D printed aortic arch template facilitates handmade fenestrations and scallops in PMSGs and may improve accuracy and quality.

Keywords

3D printing, fenestrated stent-graft, physician-modified stent-graft, surgeon-modified stent-graft, thoracic aortic aneurysm, thoracic endovascular aortic repair

Introduction

Several strategies have been proposed for extending proximal landing zones in the aortic arch for thoracic endovascular aortic repair (TEVAR), including debranching techniques,[1] chimneys,[2] in situ fenestration methods,[3] and custom-made grafts with fenestrations, scallops, or branches.[4] Manufactured grafts require time for production that limits their use in symptomatic patients. Furthermore, as some models are only for investigational use, they are not available for all vascular centers. One of the alternative is a physician-modified stent-graft (PMSG), which may be suitable for landing in zones 0 to 2.[4] However, it is a challenge during the modification to simulate the spatial distribution of target vessels because fenestrations or scallops on the stent-graft must be marked with a ruler based on measurements taken from computed tomography angiography (CTA). To facilitate this step and improve accuracy, the use of 3-dimensional (3D) printed aortic templates are proposed.

Case Report

A 73-year-old woman presented with an 86-mm descending thoracic aortic aneurysm that measured 103 mm long on CTA. There was no proximal landing zone as the aneurysm began from the level of the left subclavian artery (LSA) and extended distally to the descending thoracic aorta (Figure 1). Moreover, there was a 3-cm-wide common orifice for the left common carotid artery (LCCA) and the innominate artery (IA).

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Figure 1. (A) Left anterior oblique view and (B) reconstruction following the center lumen line of the thoracic aortic aneurysm.

The patient was disqualified for open repair by cardiac surgeons, so TEVAR was proposed using a PMSG with a fenestration for the LSA and a scallop for the combined IA-LCCA trunk. The patient gave informed consent for this nonstandard (off-label) endovascular procedure.

The plan was to create a 3D printed aortic arch based on the preprocedure CTA data to guide preparation of the PMSG. For this purpose, segmentation of the aorta was performed using Osirix (Pixmeo SARL, Bernex, Switzerland). An STL file was exported, and the mesh was corrected in Blender (Blender Foundation, Amsterdam, the Netherlands). The 3D template (Figure 2A) was printed on a Form 2 printer (Formlabs, Somerville, MA, USA) using clear resin. Postcuring was carried out with ultraviolet light; the template was then gas sterilized.

In the operating theatre, a 42×150-mm Valiant stent-graft (Medtronic, Minneapolis, MN, USA) was inserted into the 3D printed template and deployed. Using ophthalmic cautery, a fenestration for the LSA and a scallop were created (Figure 2B). After removing the stent-graft from the 3D printed template, radiopaque markers were attached. A portion of a Back-up Meier guidewire tip (Boston Scientific, Marlborough, MA, USA) was sewn around the fenestration in the shape of a loop. A figure 8–shaped radiopaque marker taken from the part of the stent-graft that was scalloped was relocated to indicate the distal end of the scallop.

The middle part of the introducer sheath was punctured with an 18-G needle (Figure 2C), and a 0.035-inch guidewire (Terumo, Tokyo, Japan) was introduced within the sheath and passed in the direction of the tapered tip (Figure 2D). Then the guidewire was passed inside the stent-graft and placed through the fenestration on the outside of the stent-graft (Figure 2E). On completing this step, the stent-graft was re-sheathed using a crimping tool (Figure 2F) taken from a set of an Edwards SAPIEN transcatheter heart valve (Edwards Lifesciences LLC, Irvine, CA, USA). During re-sheathing, special care was taken to ensure that the external part of the guidewire was in line with the fenestration because the wire also acted as an additional marker during fluoroscopy.

The next step was to flush the device with carbon dioxide.[5] In the meantime a through-and-through guidewire from the left brachial artery to the common femoral artery[6] was established. The other end of the guidewire was held close to the rear handle of the stent-graft delivery system. The TEVAR procedure with precannulated wire was performed in a method described by Joseph et al.[6] A 10×38-mm balloon-expandable covered stent (LifeStream; Bard, Tempe, AZ, USA) was used as the bridging stent to the LSA; its end was flared during postdilation. The PMSG was extended with the second component of the Valiant stent-graft in standard fashion. Both final digital subtraction angiography and 1-month follow-up CTA (Figure 3) indicated arch branch patency and no signs of endoleak. The patient was discharged a few days after surgery in good condition. After 6 months the patient is doing well. The next CTA is planned at 1 year.

Discussion

Three-dimensional printing is being increasingly used in medicine to create physical models that accurately depict complex anatomy in cardiovascular disease. Its use has already been described to assist in decision making, as well as the simulation and training of endovascular procedures.[7–10] This report details its use as a template for handmade fenestrations and scallops in the aortic arch region. Based on real anatomy, the model ensured that the fenestration and scallop were in the geometrically desired locations. There was little margin for error, contrary to a handmade spatial distribution based on estimates of length, axial clock position, and arc lengths and angles. A spatial distribution error can lead to coverage of arch branches and stroke. Since the stent-graft must be oversized in relation to the landing zone, the procedure is further challenging. Such difficulties are valid even for custom-made stent-grafts. Engineers examining the fitness of their manufactured fenestrated endografts for the abdominal aorta in 3D models suggested potential changes to 35% of the design.[11]

The curvature of the aortic arch makes the manual spatial arrangement of fenestrations even more difficult than in the case of PMSGs made for visceral aortic branches. In contrast, the method presented here does not carry any of the aforementioned risks. Another simplification of the 3D printing method is the ability to see a constellation of stents passing the arch branch ostia. Rotating the stent-graft means that the best location (without stents) can be chosen, and fenestrations or scallops can be easily created. Additionally, the advantage of clear print is that

Figure 2. (A) Three-dimensional (3D) printed model of the aortic arch. (B) Preparation of the fenestration and scallop in the 3D printed template. (C) Puncture of the introducer sheath. (D) Inserting a guidewire into the sheath (arrows). (E) Passing the wire through the fenestration. (F) Stent-graft re-sheathing with the aid of a crimping tool.

visual feedback is available regarding the stent-graft seal at the landing zone, offering one final opportunity for strategy reassessment.

Huang et al[12] were the first to describe the use of 3D printing for the preparation of fenestrations in the treatment of juxtarenal abdominal aortic aneurysm. A 3D printed template was used as an overlay for the stent-graft, which meant that fenestrations were created on a fully expanded endograft (with oversizing). This method may lead to a slight misalignment of fenestrations in vivo, contrary to the method presented here, which has the advantage of simulating stent-graft expansion in vivo, thus making it more accurate. In our opinion, the use of a 3D printed template as a single hollow tube is necessary in the aortic arch region where curvature plays a role, complicating the procedure.

Although most PMSGs are used in symptomatic patients or those with large aneurysms, the waiting time for a 3D printed template is a relatively small limitation. A desktop 3D printer is on standby at the department and capable of delivering a 3D print for surgery in only 1 day (12 hours for aortic arch printing and 9 hours for gas sterilization). However, this time delay discounts its use in the case of ruptured aneurysms.

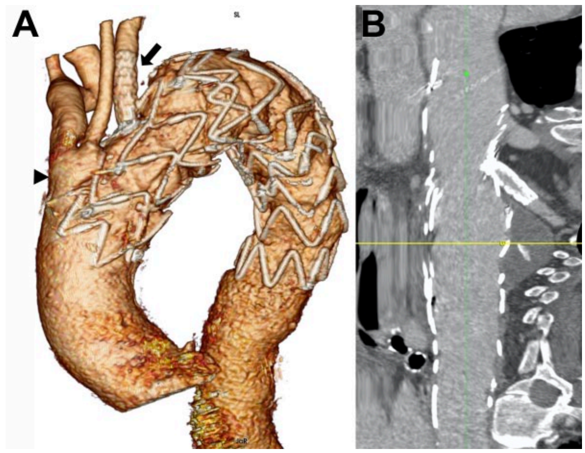

Figure 3. (A) Volumetric rendering and (B) reconstruction following the center lumen line after implantation of the physician-modified stent-graft. The linear high attenuation signal in the aneurysm sac is atherosclerotic plaque, which was seen on pretreatment computed tomography angiography and non-enhanced scans. The arrow in A points to the bridging stent through the fenestration, while the arrowhead identifies the common origin of the innominate and left common carotid arteries surrounded by the scallop.

PMSGs prolong the operation time during TEVAR. However, this delay can be shortened by the preparation of a stent-graft on the back table while the other members of the team are preparing vascular accesses and establishing a brachial-femoral through-and-through wire. Time can be saved by using a crimping tool to re-sheath the stent-graft. Compared to traditional tourniquet loops, the crimping device has the advantage of symmetrically reducing the stent-graft diameter as it is being packed in a sheath. This ensures that all radiopaque markers, scallops, and fenestrations are in the desired position. Torquing those structures could lead to misalignment error during implantation.

The TEVAR procedure with a PMSG can be associated with additional operative risks. The main concern for endovascular interventions in the aortic arch region is perioperative stroke. Beside plaque embolization from manipulation in the aortic arch, air emboli originating from stent-graft sheaths have been described.[5] Since there is a lot of air in the sheath after re-sheathing a PMSG, flushing with carbon dioxide is strongly recommended.[13]

The other procedural risk is the possibility of stent-graft infection. Therefore, all stent-graft modifications must be carried out carefully in a sterile environment in the shortest possible time. The 3D printed template must be sterilized beforehand. The recommended method of 3D printed template sterilization is gas, which does not affect the model structure. Heat sterilization could deform the vascular replica, leading to an error during stent-graft modifications.

The limitation of the proposed model is that aortic anatomy may change after the insertion of a semi-rigid stent-graft into the aortic lumen and thus alter the alignment of the side branches. This same issue is valid for custom-made devices and other PMSGs that are based on CTA measurements. At this moment we are not able to predict aortic elongation and angulation based on CTA calculations. However, in the presented case we did not observe a misalignment of the fenestration or scallop, which may be due to the fact that the aortic arch fixation points are the sites of origin of major branch vessels.

The future direction of endovascular simulations could be the creation of elastic models that would offer an elastic modulus similar to the average aortic wall. Such replicas should have the same fixation points as the aorta. Those models could be used for the creation of a PMSG and also implemented in the design of custom-made devices to improve their accuracy. This may be particularly important in the visceral aorta where aortic angulation could lead to fenestration misalignment due to the straightening of the aorta after introducing the stent-graft.

Conclusion

Three-dimensional printing is emerging as the perfect template for handmade fenestrations, as well as offering an improvement in accuracy and quality. It is a commonly available technology and offers relatively short production turnaround, meaning it is an excellent adjunctive tool for the preparation of PMSGs.

Declaration of Conflicting Interests

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