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ORIGINAL RESEARCH ARTICLE

New imaging technologies for complex aortic aneurysms diagnosis and treatment

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ABSTRACT

Imaging technology plays a key role in guiding endovascular treatment of aortic aneurysm, especially in the complex thoracoabdominal aorta. The combination of high quality images with a sterile and functional environment in the surgical suite can reduce contrast and radiation exposure for both patient and operator, in addition to better outcomes. This presentation aims to describe the current use of this technique, combining angiotomography and intraoperative cone beam computed tomography, image "fusion" and intravascular ultrasound, to guide procedures and thus improve the intraoperative success rate and reduce the need for reoperation. On the other hand, a procedure is described to create customized 3D templates with the high-definition images of the patient's arterial anatomy, which serve as specific guides for making fenestrated stents in the operating room. These customized fenestration templates could expand the number of patients with complex aneurysms treated minimally invasively.

Keywords: Abdominal Aortic Aneurysm; Endovascular Procedures; Intraoperative Imaging; CBCT; Image Fusion

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1. Introduction

Improvements in endovascular technologies and the development of standard or custom-made stents now allow us to treat complex aortic lesions, such as dissections or thoracoabdominal aneurysms[1–3]. These advances are leading to an increase in the complexity of endovascular procedures, which implies the need for greater precision and image quality, long procedure times and high levels of radiation exposure[4,5]. At the same time, pressure is exerted on professionals dedicated to vascular surgery to show increasingly efficient interventional skills and radiological practices.

In this context, advanced imaging technology represents a solid pillar in the toolbox designed to provide the best care with the least risk.

Based on this technology, we present in this article our initial experience with the repair of complex aortic aneurysms by endovascular placement of custom-made fenestrated stents in the operating room, using three-dimensional impression molds.

The presentation is divided into two sections: planning and procedure.

2. Imaging technologies for surgical planning

2.1 Dual energy tomography

Computed tomography with dual energy technology consists of the acquisition of images through variable levels of X-ray energy and its comparison. Depending on the technology used, the acquisition may be through the emission by two X-ray sources, a single emitting source with a Kv switching or with spectral detector technology that allows utilization of higher and lower energy X-rays in a single scan.

Knowing how a particular substance behaves at two different X-ray energies can provide information about tissue composition beyond what can be inferred with techniques that employ a single X-ray energy level. The new dual-energy tomography (spectral CT) has become a promising tool with multiple clinical applications[3–6]. With its ability to characterize elements on the basis of the comparison between the photoelectric effect and the Compton effect, it allows the differential attenuation of tissues and materials and can help to identify the composition of structures, among which we can count the differentiation between intravascular iodine from calcified atherosclerotic plaques or surgical materials on the basis of their differential attenuation values. In addition, dual-energy CT is able to substantially reduce artifacts caused by metallic prostheses, remove calcium from calcified atherosclerotic plaques and improve the assessment of the degree of stenosis.

By increasing the visibility of iodine, contrast-enhanced dual-energy CT can make an endoleak more evident compared with conventional CT, distinguishing it from surgical materials (coils or stents). Another advantage of low-KeV reconstruction is that it can also be used to amplify the density of EV contrast in angiographic studies with luminal opacities, whether in patients with poor ventricular function, when embolization of contrast fails or is partially extravasated, or in patients with low contrast use related to pre-existing medical conditions. Finally, it greatly reduces the radiation dose to the patient as it does not require a first non-contrast acquisition.

2.2 Endovascular repair of complex aneurysms using fenestrated stents constructed in the operating room by three-dimensional printing

Endovascular repair of aneurysms by fenestrated stents is frequently used for juxtarenal aortic, pararenal and thoracoabdominal aneurysms. Currently, after a thorough analysis of the arterial anatomy, devices are being constructed industrially that, by means of fenestrations (orifices), make it possible to incorporate the visceral segment of the aorta within the territory to be covered. Unfortunately, it is necessary to wait about 8 to 10 weeks for these devices, which makes their use impractical in urgent cases[6,7]. As a solution to this problem, stents modified by the physician in the operating room can be implanted from a standard graft, making the fenestrations according to the patient's anatomy. But this requires precise planning. Despite experience, there is always a margin of error. The possibility of misalignment between the fenestration and the ostium of the vessel to be respected can lead to longer cannulation time and complications at the time of stent placement, including vessel loss.

On the other hand, we recognize that the relatively slow uptake of fenestrated stent technology is related, at least in part, to case planning and procedural complexity. A critical evaluation of the applicability of this technique requires an understanding of how, for example, aortic angulation affects fenestration distance measurements. The planning of fenestrations in aortic anatomy with slight angulation is fairly straightforward, and the results should be similar between conventional software planning and the plan generated by a 3D anatomical reproduction of the patient's aorta. However, most patients with juxtarenal aneurysms have visceral aortas that are angulated, up to 60 degrees or more. We have learned that it is important to take into account the alteration in the aortic axis, which means placing a rigid guidewire and introducer with the stent inside and the aorta angled. Failure to perform this centerline adjustment leads to significant errors in the distance measurements required to correctly place the fenestrations. As a consequence, this error leads to difficult cannulation of the branch during implant placement. With highly angulated juxtarenal aneurysms, such fenestration discrepancies of 1 to 3 mm appear between the conventional plane and the imprecise 3D template. It is thus tempting to print an exact replica of the visceral aorta for planning purposes, introducing the aortic angulation, to correctly align the stent holes to the artery to be respected.

Three-dimensional aortic printing has been widely described in medicine for simulation, training and surgical planning[8,9].

We describe an effective technique that uses computer-aided design software to create a real 1:1 3D aortic model, which can be easily printed and quickly sterilized. For this purpose, an external provider (MIRAI 3D, Buenos Aires) associated with our institutions performed the modeling and printing. To generate a 3D model for the prosthesis mold, a CT scan with arterial contrast was used as the starting point. Using anatomical structure segmentation software, a contrast scan is performed on the patient's CT scan, leaving only the aorta and its branches visible. On this model a smoothing is applied with organic 3D modeling software. Using the aorta as a base, normal guides are placed at the exits of the renal arteries, the superior mesenteric artery and the celiac trunk. By extruding the walls of the aorta, the mold is generated, which will then be printed. The outlets of the arteries are cut out. Once the molds are generated, stereolithography technology is chosen for printing the models, since it provides a superior finish to FDM (fused deposition modeling) technologies. The Form 2 printer from Formlabs is used, using "Clear" resin for the rigid models and "Elastic" resin (with a hardness of 50 A Shore and elongation of 160%) for the flexible models. A customized template is then created to serve as a patient-specific guide for graft fenestration. It is sterilized by hydrogen peroxide plasma in Sterrad equipment, with an express cycle, which allows rapid sterilization of delicate materials. With the impression already prepared, the standard stent is placed inside the model, unfolded, and the locations of the model openings (fenestrations) are marked with a sterile pen on the stent. The fenestrations are made with an electrocautery device and reinforced with a strong, radiopaque material to allow visualization with X-rays (**Figure 1**).

This aortic model is used to create a precisely fenestrated stent graft, with the potential to generate shorter and safer procedures. Although this is an initial experience, several publications have shown 3D printing to be a valuable tool for planning, designing and creating devices with greater accuracy.

It is also an effective tool for teaching and training physicians in complex procedures, thus reducing the learning curve. Simulating all complicated surgical steps in advance, using prototype models, can help predict intra- and postoperative complications. This is another use, which, together with videoconferencing technologies, is being developed in our environment. Some studies show how 3D visualization, instead of 2D screen, has helped in operational pre-planning, both to choose the path and to modify a previously made decision. 3D printing, in these cases, is used to improve visualization. For that, we also design models, in order to show different technical and tactical alternatives for complex treatments. By means of 3D printing of real cases, we are remotely training on fine technical details in endo-prosthesis placement. These real 3D models replicate the exact anatomy of the diseased aorta, with a clear image of the pathological process (**Figure 2**).

Finally, by using 3D printing, surgeons can more easily explain to patients their clinical situation and the type of surgery they will undergo. Recent publications have shown that the use of 3D printing contributes positively to strengthening the decision that patients make and increases their "consensus" for surgical treatment (**Figure 2**).

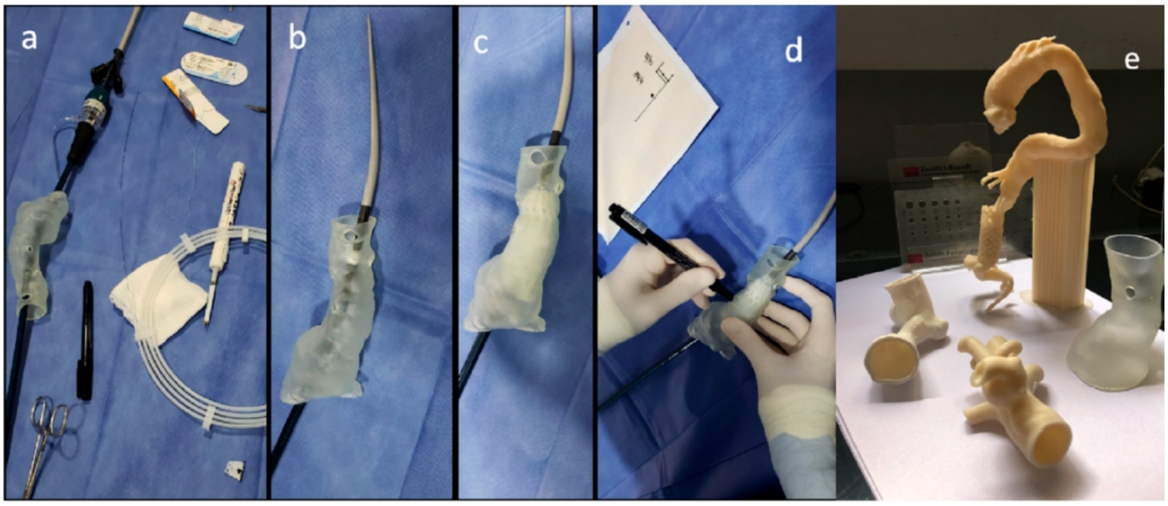

Figure 1. Different materials and steps necessary to make a fenestration in a patient with renal arteries at the proximal neck level, in the plan for placement of a fenestrated stent (**a**–**d**). Some 3D printing models (**e**), manufactured for different purposes (fenestrations, patient information, surgical tactics).

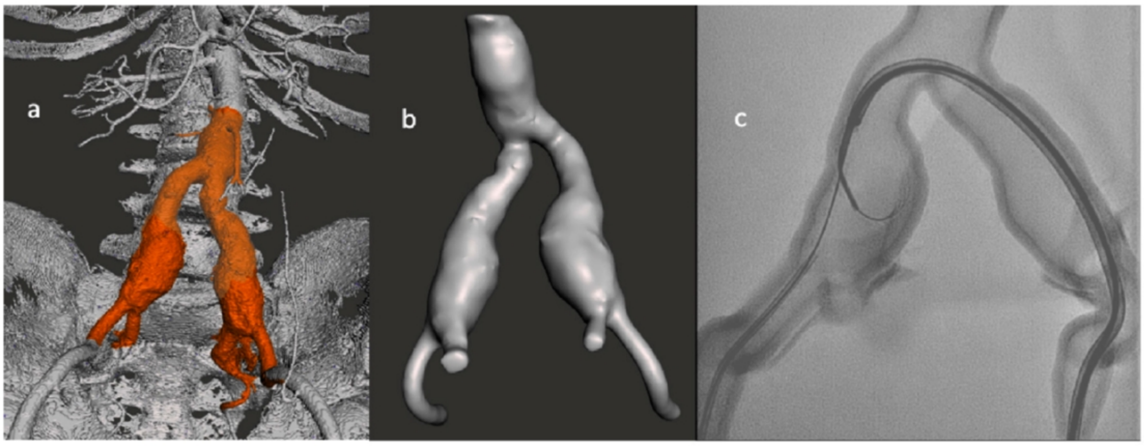

Figure 2. Tomographic image (**a**) from which the 3D impression is extracted (**b**). This impression is used for training in iliac branched endoprosthesis placement (**c**).

3. Useful imaging technologies during the procedure

During the implantation of an endoprosthesis there are four imaging tools that are fundamental for us to obtain a good result and at the same time taking care of the patient and the treating team. Imaging plays a critical role in all phases of endovascular treatment of aortic aneurysm, from planning through placement to follow-up. While advanced imaging modalities have become routine for the planning and follow-up phases after complex procedures in particular, angiography and fluoroscopy have remained the intraoperative imaging techniques of choice for many years. The introduction of advanced intraoperative imaging for procedural guidance and control has the potential to reduce the perioperative use of contrast and radiation, to improve intraoperative success and to decrease the need for secondary postoperative interventions. The application of these techniques obviously requires advanced imaging equipment within the operating room.

3.1 Low radiation imaging systems

Modern equipment has a 48-inch flat panel detector that captures information with four times the resolution of conventional X-ray systems, with image display, multimodality access, hemodynamic monitoring and integrated reporting. They generate a comprehensive 3D visualization of pathologies from a single rotational angiography performed in a few seconds. But probably the most important of these advances is the ClarityIQ technology, which is the latest breakthrough in reducing radiation exposure for patients and medical staff. This technology maintains equivalent image quality at a radically lower dose level. This helps reduce radiation dose as a barrier to new and more complex procedures and techniques.

3.2 Vessel Navigator or image fusion

Our state-of-the-art rooms are equipped with a wide range of new imaging applications, such as fusion imaging and cone beam computed tomography (CBCT). These technologies contribute to radiation reduction through software that enables complex, safe and efficient endovascular procedures. One of the greatest strengths of this technology is image fusion. By means of specially designed software, previously captured tomography images can be fused with live images obtained in the operating room by radioscopy. In other words, without injecting contrast, it is possible to know where the stent should be deployed, or where the renal artery is, on which its respective fenestration should be left[8-11]. Fusion imaging involves four steps to achieve optimal intraoperative placement: processing of the preoperative computed tomography angiography (CTA), selection of landmarks on the preoperative CTA, acquisition of an intraoperative volume using CBCT, and fusion between the intraoperatively obtained image (CBCT) and the preoperative CTA. In this way, surgery time is significantly shortened and the amount of contrast material and radiation dose is reduced (**Figure 3**).

3.3 Intravascular ultrasonography

Intravascular ultrasonography (IVUS) allows real-time imaging of the vessel and is ideal for aortic interventions. IVUS provides accurate information to assess access routes, location and distances between branches of the aorta, as well as vessel size, to determine graft size or associated lesions, which facilitates the performance of complex aortic endovascular procedures. Moreover, the use of IVUS reduces the need for high doses of contrast and radiation in most procedures, as it replaces angiography in many instances. IVUS gives us the reassurance of navigating in the true light, in the case of both acute and chronic dissections (**Figure 4**). Together with the 3D roadmap based on fusion techniques, IVUS can locate the entry and reentry tears, the flow in the false lumen and the size of the respective lumens, even before fluoroscopy. These images, which can also be saved, can be used as a guide (based on bony landmarks) for the correct deployment of the stent[12,13].

3.4 Intraoperative CBCT

A final angiogram can sometimes have difficulty detecting stenosis in the iliac limbs of a stent, or the accommodation of a stent within the renal artery, in the case of branched stents. To detect defects, it is necessary to perform multiple projections. CBCT is the same tomography performed to cali-

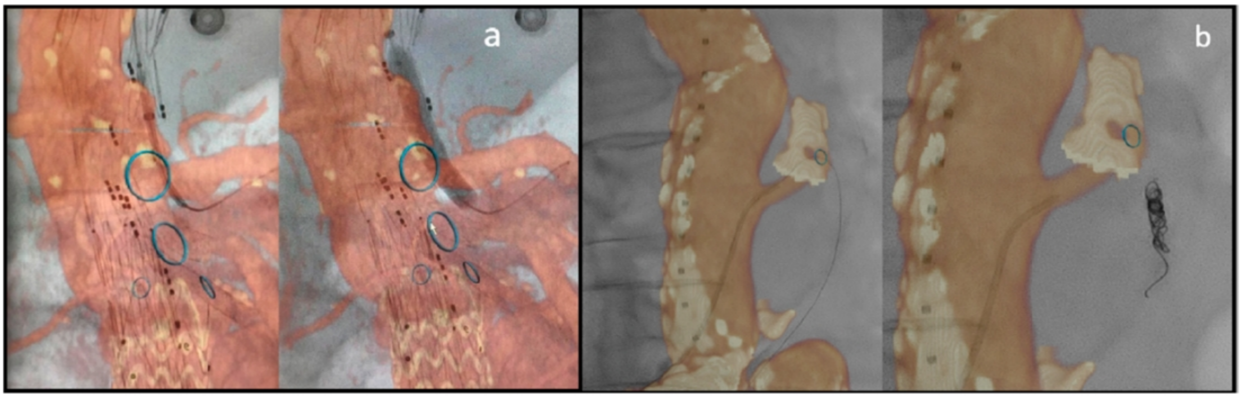

Figure 3. Two sequences in which image fusion was used. In the one on the left (**a**), the image in shades of orange, corresponding to the previous angio-CT, is fused with the image in shades of gray, corresponding to the live angiographic image. The celiac trunk is cannulated in the case of a branched stent. In the image on the right (**b**), the light blue ring shows the origin of the inferior mesenteric artery to be embolized with coils to avoid a type II endoleak.

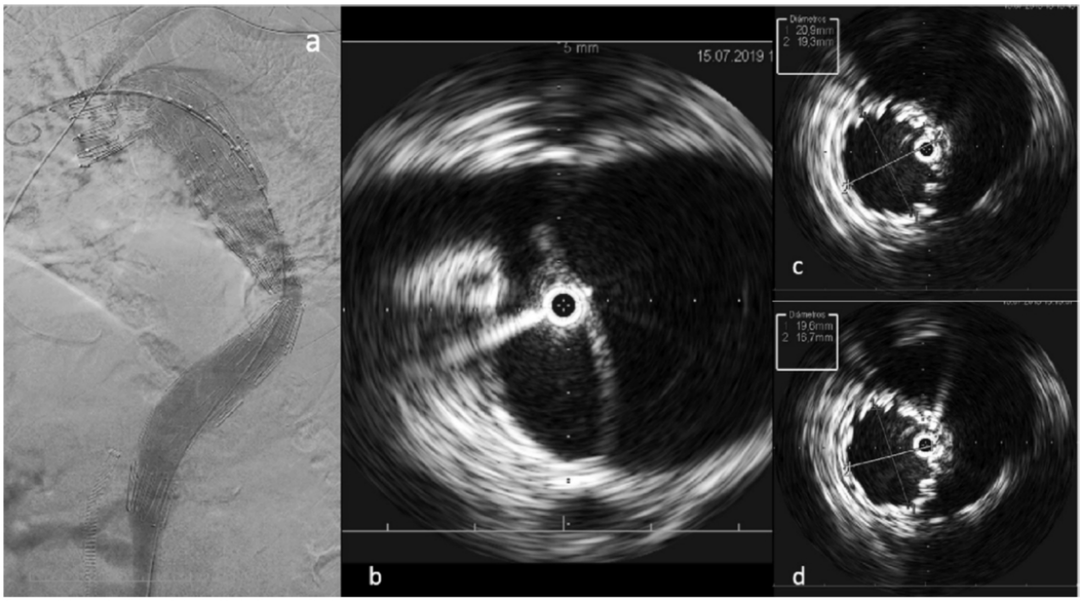

Figure 4. Intravascular ultrasound image. Final angiography demonstrating exclusion of the false lumen in a patient with a type B aortic dissection (**a**). IVUS images show that the guidewire through which the stent should travel is in the true lumen (**b**) and furthermore, that the true lumen expands along several segments of the aorta after placement of the stent occluding the dissection entry orifice (**c**–**d**).

brate the fusion, but it is performed at the end of the surgery. Without contrast, with very low radiation dose, it is especially useful to detect uncoupling between stents or with contrast injection for the detection of endoleaks or incorrect alignment of the stent with the artery in which it is placed. Intraoperative detection of these complications avoid reinterventions[14]. Likewise, CBCT and its use in conjunction with fusion can facilitate successful embolization in type II endoleaks with complex circulation[15].

4. Conclusion

Several advanced imaging solutions are now available to help treat complex aortic aneurysms. Based on our experience with the routine use of these applications in a hybrid room, we recommend adopting these types of technologies with a clear clinical benefit for the patient.

On the other hand, 3D custom molds provide us with the fast and accurate information needed to fabricate custom stents without the need for manual measurements based on a standard endovascular graft. This technique has the potential to make endovascular aortic aneurysm repair available to more patients with challenging anatomy.

Ethical considerations

The procedures carried out are in accordance with the ethical standards of the local committee of both institutions.

Conflict of interest

The authors declare that they have no conflicts of interest.

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