SPECIAL ARTICLE

New Imaging Technologies for the Diagnosis and Treatment of Complex Aortic Aneurysms

Nuevas tecnologías de imágenes para el diagnóstico y tratamiento de los aneurismas de aorta complejos

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ABSTRACT

Imaging technology plays a key guiding role in the endovascular treatment of aortic aneurysms, especially in cases of complex thoracoabdominal aortic aneurysms. The operating rooms combine high quality imaging with a sterile and functional environment, allowing for better outcomes, a reduction of the contrast agent to be used and of patients' and operators' exposure to radiation. The aim of this presentation is to describe the current use of imaging technology, combining intraoperative cone beam computed tomography (CBCT) and computed tomography angiography (CTA), image "fusion" and intravascular ultrasound, to guide the procedures and thus improve the intraoperative success rate and reduce the need for reinterventions. Also, a procedure to create custom 3D templates with high-definition images of the patient's arterial anatomy is described, which serve as specific guides to develop fenestrated stent-grafts in the operating room. These custom fenestration templates could increase the number of patients with complex aneurysms treated with a minimally invasive approach.

Key Words: Aortic Aneurysm, Abdominal - Endovascular Procedures - Intraoperative Images - CBCT - Image Fusion

RESUMEN

La tecnología en imágenes desempeña un papel fundamental como guía en el tratamiento endovascular del aneurisma de aorta, especialmente en la aorta compleja toracoabdominal. Las salas quirúrgicas combinan imágenes de alta calidad con un entorno estéril y funcional, lo que permite, además de mejores resultados, una reducción del contraste a utilizar y la exposición a la radiación de pacientes y operadores. Esta presentación tiene como objetivo describir el uso actual de dicha tecnología, combinando angiotomografía y tomografía computarizada de haz cónico intraoperatoria, la "fusión"de imágenes y la ecografía intravascular, para guiar procedimientos y así mejorar la tasa de éxito intraoperatorio y reducir la necesidad de reintervenciones. Por otro lado, se describe un procedimiento para crear plantillas personalizadas 3D con las imágenes de alta definición de la anatomía arterial del paciente, que sirven como guías específicas para confeccionar en quirófano endoprótesis fenestradas. Estas plantillas de fenestración personalizadas podrían ampliar el número de pacientes con aneurismas complejos tratados en forma mínimamente invasiva.

Palabras clave: Aneurisma de la aorta abdominal - Procedimientos endovasculares - Imágenes intraoperatorias - CBCT - Fusión de imágenes

INTRODUCTION

Today, improvements in endovascular technologies and the development of standard or customized stent-grafts allow us to treat complex aortic lesions, such as dissections or thoracoabdominal aneurysms. (1-3) These advances result in more complex endovascular procedures, with the need for greater accuracy and quality of images, longer procedural times, and high levels of radiation exposure. (4, 5) In turn, pressure is exerted on cardiovascular surgeons to show increasingly efficient interventional skills and radiology practices.

In this context, advanced imaging technology represents a solid mainstay in the set of tools aimed at providing the best care with minimal risk.

Based on this technology, this article describes our initial experience with complex aortic aneurysm repair by endovascular implantation of a customized fenestrated stent-graft created in the operating room, using 3D-printed templates.

We have divided the presentation into two sections: planning and procedure.

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Imaging technology for surgical planning

Dual-energy computed tomography

Dual-energy computed tomography (DECT) consists of image acquisition and comparison through variable X-ray energy levels. Depending on the technology used, the acquisition may be through dual-source X-rays, single-source with Kv switching or spectral detector technology, which takes advantage of high- and low-energy X-rays in a single scan.

Knowing how a certain substance behaves with two different X-ray energies can provide information about tissue composition, apart from the information that can be inferred from a single X-ray energy technique. The novel dual-energy computed tomography (spectral CT) has become a promising tool with multiple clinical applications. (3-6) With its capacity of characterizing elements by comparing the photoelectric and Compton effects, it allows for differential attenuation of tissues and materials, and can help determine the composition of structures, including the differentiation of intravascular iodinated contrast material of calcified atherosclerotic plaques or surgical materials, based on their differential attenuation values. Moreover, dual-energy CT scan is capable of substantially reducing artifacts caused by metallic endografts, and of removing calcium from calcified atherosclerotic plaques, thus improving the assessment of the degree of stenosis.

By increasing the visibility of iodine, contrast-enhanced dual-energy CT can render an area of endoleak more visible compared with conventional CT, differentiating it from surgical materials (coils or stents). An additional advantage of low KeV reconstruction is that it can also be used to enhance IV contrast material density in angiographic studies with suboptimal vessel lumen opacification, either in patients with poor ventricular function, poor bolus timing, or partial extravasation of the contrast material, or in patients receiving reduced contrast material due to pre-existing medical conditions. Finally, it substantially reduces the radiation dose delivered to the patient by eliminating the need for a first nonenhanced acquisition.

Complex endovascular aneurysm repair using fenestrated stent-grafts created in the operating room by 3D-printing

Endovascular aneurysm repair using fenestrated stent-grafts is often used for juxtarenal, pararenal, and thoracoabdominal aortic aneurysms. Nowadays, after a deep analysis of the arterial anatomy, industrially manufactured devices, by means of fenestrations (orifices), allow for the incorporation of the visceral segment of the aorta within the territory to be covered. Unfortunately, the waiting time for these devices is between eight and ten weeks, turning their use impracticable in urgent cases. (6, 7) To solve this problem, stent-grafts modified from a standard graft in the operating room by the physician can be implanted, making the fenestrations according to the patient's anatomy. However, it requires accurate planning. Despite experience, a margin of error always exists, and a mismatch possibility between the fenestration and vessel ostium can lead to increased cannulation time and stent implantation complications, including target vessel loss.

On the other hand, we agree that the relatively slow adoption of fenestrated stent-graft technology relates –at least in part– to case planning and procedural complexity. A critical assessment of the applicability of this technique requires understanding of how, for instance, aortic angulation affects fenestration distance measurements. Planning fenestrations in aortic anatomy with slight angulation is fairly straightforward, and results should be similar between conventional software planning and the plan generated by a 3D anatomic reproduction of the patient's aorta. However, most juxtarenal patients have angulated visceral aortas, of up to 60 degrees or more. We have learned that it is important to account for the altered aortic axis, which means the interaction between the stiff guidewire and endograft delivery system and the angulated aorta. Failure to make this centerline adjustment leads to significant errors in the distance measurements required to properly locate fenestrations and consequently leads to difficult branch vessel cannulation during implant delivery. In juxtarenal aneurysms with large angulation, such fenestration discrepancies of 1 to 3 mm between the conventional plan and the 3D printed template are observed. It is tempting to print an exact replica of the visceral aorta for planning purposes, introducing the aortic angulation in order to properly align the fenestrations with the intended artery.

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

We describe an effective technique that uses a computer-aided design software to create a real 1:1 3D aortic model that can be easily printed and quickly sterilized. For that purpose, an external supplier (MIRAI 3D, Buenos Aires) associated with our institutions carried out the modeling and printing. To create a 3D model for the graft template, the starting point is a contrast-enhanced CT scan. Using software for segmentation of anatomical structures, a contrast scan is performed on the patient's tomography, leaving visible only the aorta and its branches. On this model, smoothing is applied with an organic 3D-modeling software. Using the aorta as a base, normal guidewires are placed at the exit of the renal arteries, the superior mesenteric artery and the celiac trunk. Extruding the aortic walls creates the template, which will then be printed. The artery exits are cut. Once the templates are obtained, stereolithography is chosen for model printing, since it provides a superior finish to FDM (fused deposition modeling) technology. A Form 2 printer (Formlabs Company) is used; "Clear" resin is utilized for the rigid models, and "Elastic" resin (with a hardness of 50A Shore and elongation of 160%) for the flexible models. A custom template is created that serves as the patient's specific guide for graft fenestration. It is sterilized by hydrogen peroxide plasma in a STERRAD® system using the express cycle feature, which allows the rapid sterilization of delicate materials. Once the printing is ready, the standard stent-graft is deployed inside the model, and the opening (fenestrations) locations are marked on the stent-graft with a sterile pen. Fenestrations are cut with an electrocautery device, and reinforced with a resistant, radiopaque material for visualization with X-rays (Figure 1).

This aortic model is used to create an accurate fenestrated stent-graft, potentially leading to shorter and safer procedures. While this is an initial experience, various 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 training physicians in complex procedures, thus reducing the learning curve. Simulating all the complicated surgical steps in advance using prototype models can help prevent intra- and postoperative complications. This other use is being developed in our environment, together with videoconferencing technologies. Some studies show how 3D visualization –instead of the 2D screen– has helped in surgical pre-planning, both to choose the path and modify a previously made decision. In these cases, 3D printing is used to improve visualization. For this purpose, we also design models, in order to show different technical and tactical options for complex treatments. Through 3D impressions of real cases, we are providing remote training on fine technical details in stent-graft delivery. Real 3D models replicate the exact anatomy of the diseased aorta, with a clear image of the pathological process (Figure 2).

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

Useful intraoperative imaging technologies

During stent-graft delivery, four imaging tools are essential to obtain a good result and at the same time care for the patient and the attending team. Imaging plays a key role in all the phases of endovascular aortic aneurysm repair, from planning, all through delivery, to follow-up. While advanced imaging modalities have routinely been used for the planning and follow-up phases after complex procedures, angiography and fluoroscopy in particular have remained the intraoperative imaging techniques of choice for many years. The introduction of advanced intraoperative imaging to guide and control the procedure has the potential to reduce perioperative use of contrast material and radiation, improve intraoperative success, and reduce the need for secondary postoperative interventions. Undoubtedly, the use of these techniques requires advanced imaging equipment within the operating room.

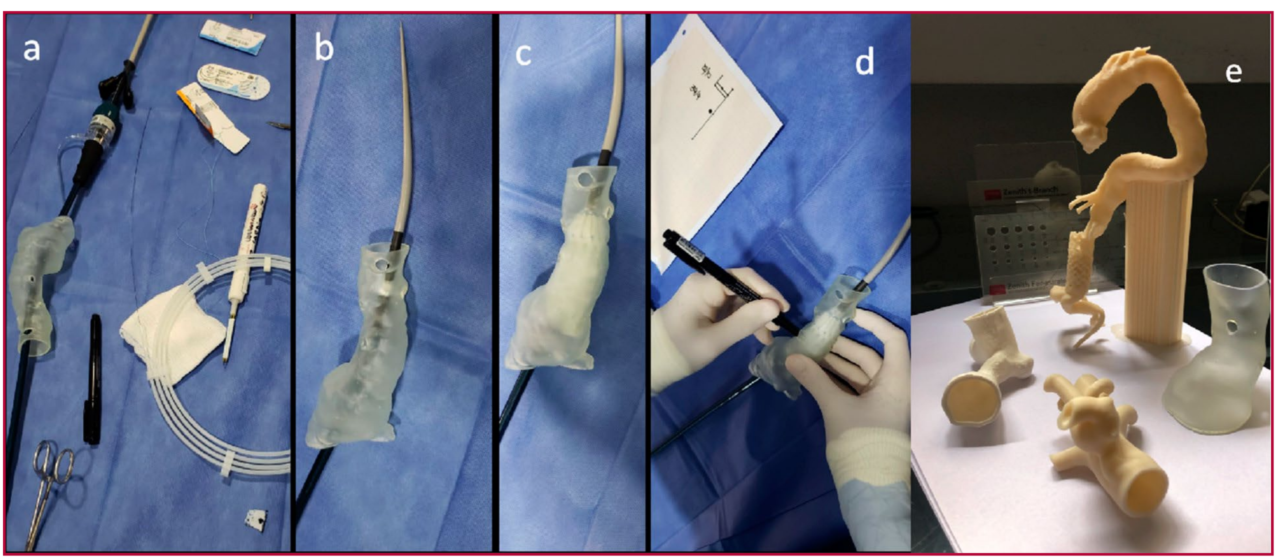

Fig. 1. Different materials and necessary steps to create a fenestration in a patient with the renal arteries at the level of the proximal neck, in whom a fenestrated stent-graft implantation is planned (a-d). Some 3D-printed models (e), manufactured for different purposes (fenestrations, patient information, surgical approach).

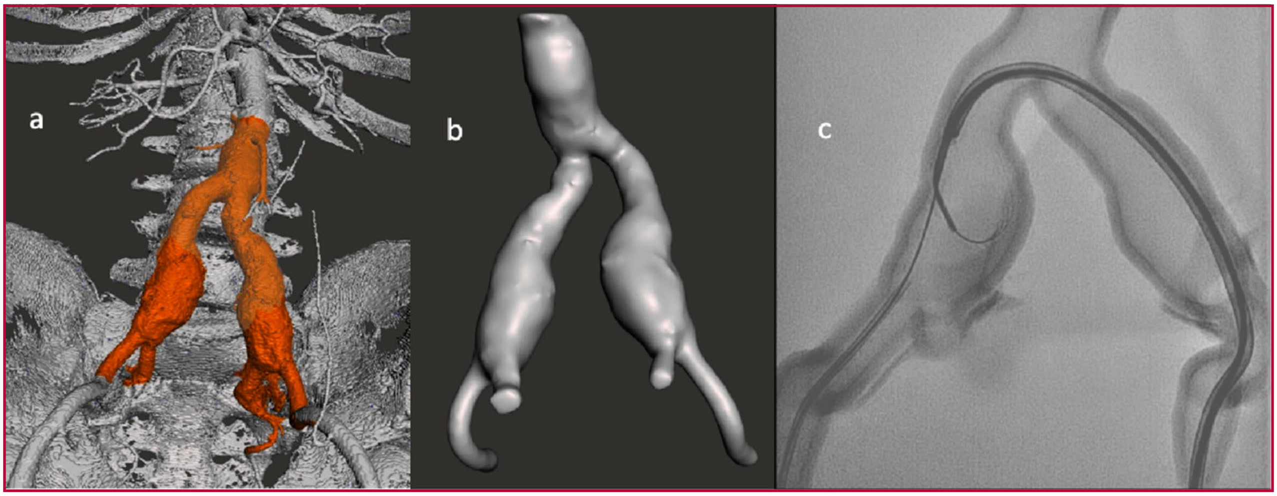

Fig. 2. CT image (a) from which the 3D-impression is obtained. This impression is used for training in iliac branched stent-graft implantation (c)

Low radiation imaging systems

Modern systems have a 48-inch flat panel detector, which captures information that is four times the resolution of conventional X-ray systems, and includes image display, multimodal access, hemodynamic monitoring, and integrated reports. These systems generate extensive 3D visualization of pathologies from a single rotational angiography run in a few seconds. However, the most important of these advances is probably ClarityIQ technology, the latest breakthrough in lowering radiation exposure for patients and medical staff. This technology provides equivalent quality imaging with significantly lower dose radiation levels. This helps reduce X-ray doses as a barrier for new and more complex procedures and techniques.

Vessel Navigator or fusion imaging

Our modern operating 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 lowering X-ray doses through a software that allows for safe and efficient complex endovascular procedures. One of the greatest virtues of this technology is fusion imaging. Using a specially designed software, previously acquired tomography images can be merged with live images obtained by radioscopy in the operating room. In other words, it is possible to know, without contrast injection, where the stent-graft should be deployed or where the origin of the renal artery is to match its respective fenestration. (8-11) Fusion imaging involves four steps to achieve optimal intraoperative delivery: preoperative computed tomography angiography (CTA) processing, preoperative selection of CTA landmarks, intraoperative volume acquisition using CBCT, and intraoperative CBCT and preoperative CTA imaging fusion. In this way, surgery time is significantly shortened and the amount of contrast agent and radiation dose are reduced (Figure 3).

Intravascular ultrasound

Intravascular ultrasound (IVUS) allows for real-time imaging of the vessel, and is ideal for aortic surgery. It provides accurate information to assess pathways, location and distances between aortic branches, and also vessel size to determine graft size or associated lesions, facilitating complex aortic endovascular procedures. Furthermore, as it replaces angiography in many cases, IVUS reduces X-ray and contrast exposure in most procedures and ensures the ability to navigate in the true lumen, both in acute and chronic dissections (Figure 4). Together with the 3D-roadmap based on fusion techniques, IVUS can locate entry and re-entry tears, flow in the false lumen, and the size of the respective lumens, even before fluoroscopy. These images can also be saved and used as a guide (based on bone landmarks) for correct stent-graft deployment. (12, 13)

Intraoperative cone beam computed tomography

A final angiography can sometimes have difficulty to detect stenosis in the iliac limbs of an aortic endograft, or stent fit within the renal artery in the case of branched stent-grafts. Multiple projections are required to detect defects. Cone beam computed tomography is the same tomography that is performed for fusion calibration, but at the end of surgery. Without contrast and with a very low radiation dose, CBCT is used specially to detect stent mismatch; with contrast injection, it is used to detect endoleaks or stent-graft misalignment with the artery in which it is deployed. Intraoperative recognition of these complications avoids reinterventions. (14) Similarly, CBCT and its use in combination with fusion facilitates successful embolization in complex type II endoleaks. (15)

Ethical considerations

The procedures have been performed in accordance with the local Ethics Committee standards of both institutions.

CONCLUSION

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

Furthermore, custom 3D templates provide us with fast and accurate information to manufacture customized stent-grafts based on a standard endovas-

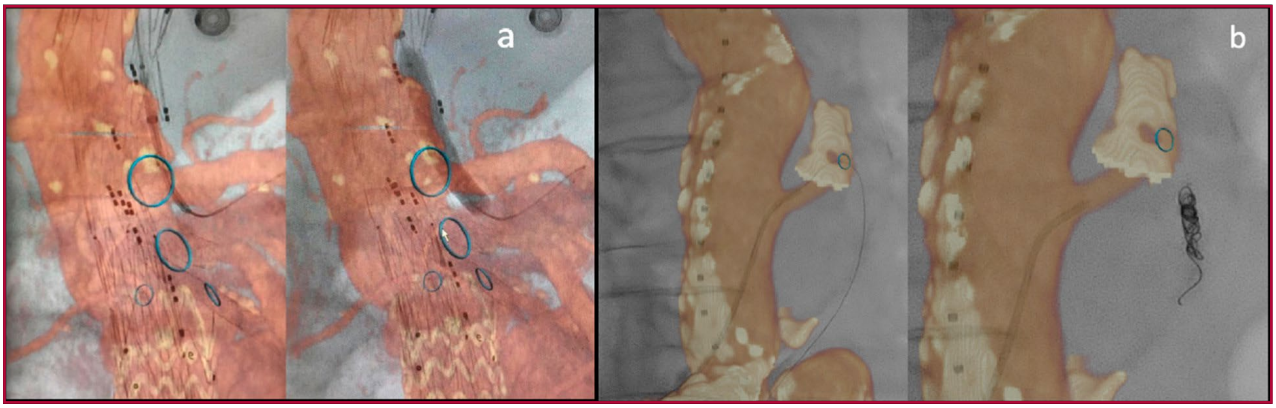

Fig. 3. Two sequences in which fusion imaging was used. On the left (a), the orange image –corresponding to the previous CT-angiography– is merged with the gray image –corresponding to the live angiography. The celiac trunk is cannulated in the case of a branched stent-graft. On the right (b), the light-blue ring shows the origin of the inferior mesenteric artery to be embolized with coils to avoid type II endoleak

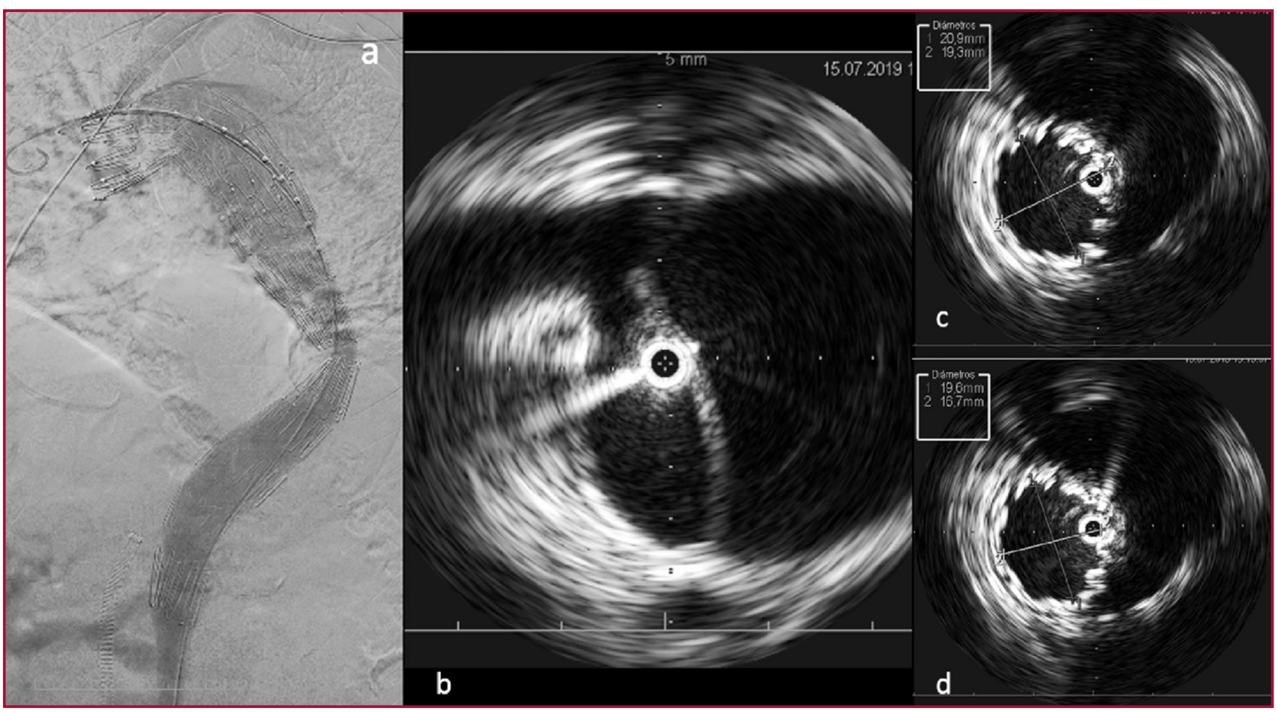

Fig. 4. Intravascular ultrasound image. Final angiography showing the exclusion of false lumen in a patient with a type B aortic dissection (a). IVUS images show that the guidewire through which the stent-graft should be delivered is in the true lumen (b), and that the true lumen expands along several segments of the aorta after the stent-graft which occludes the entry orifice of the dissection is implanted (c-d).

cular graft, without the need for manual measurements. This technique has the potential to make endovascular aortic aneurysm repair available to more patients with challenging anatomy.

Conflicts of interest

None declared.

(See authors' conflicts of interest forms on the website/ Supplementary material)

REFERENCES

1. Tenorio ER, Lima GB, Marcondes GB, Oderich GS. Sizing and planning fenestrated and branched stent-grafts in patients with chronic post-dissection thoracoabdominal aortic aneurysms. J Cardiovasc Surg (Torino) 2020;61:416-426. http://doi.org/10.23736/S0021-9509.20.11365-X.

2. Katsargyris A, Uthayakumar V, Marques de Marino P, Botos B, Verhoeven EL. Aneurysm Rupture and Mortality During the Waiting Time for a Customised Fenestrated/Branched Stent Graft in Complex Endovascular Aortic Repair. Eur J Vasc Endovasc Surg. 2020;60:44-8. 10.1016/j.ejvs.2020.03.003.

3. Duan X, Ananthakrishnan L, Guild JB, Xi Y, Rajiah P. Radiation doses and image quality of abdominal CT scans at different patient sizes using spectral detector CT scanner: a phantom and clinical study. Abdom Radiol (NY) 2020;45:3361-8. http://doi.org/10.1007/s00261-019-02247-1.

4. Skawran S, Angst F, Blüthgen C, Eberhard M, Kälin P, Kobe A, et al. Dual-Energy Low-keV or Single-Energy Low-kV CT for Endoleak Detection: A 6-Reader Study in an Aortic Aneurysm Phantom. Invest Radiol 2020;55:45-52. http://doi.org/10.1097/RLI.0000000000000606.

5. Martin SS, Wichmann JL, Weyer H, Scholtz JE, Leithner D, Spandorfer A, et al. Endoleaks after endovascular aortic aneurysm repair: Improved detection with noise-optimized virtual monoenergetic dual-energy CT. Eur J Radiol 2017;94:125-32. http://doi.org/10.1016/j.ejrad.2017.06.017.

6. Meess KM, Izzo RL, Dryjski ML, Curl RE, Harris LE, Springer M, et al. 3D Printed Abdominal Aortic Aneurysm Phantom for Image Guided Surgical Planning with a Patient Specific Fenestrated Endovascular Graft System. Proc SPIE Int Soc Opt Eng 2017. http://doi.org/10.1117/12.2253902.

7. Starnes BW. Three-dimensional printed templates to guide fenestrated endovascular aneurysm repair are not as straightforward as they appear. J Vasc Surg Cases Innov Tech 2020;6:104-5. http://doi.org/10.1016/j.jvscit.2019.12.002

8. Gallitto E, Faggioli G, Vacirca A, Pini R, Mascoli C, Fenelli C, et al.The benefit of combined carbon dioxide automated angiography and fusion imaging in preserving perioperative renal function in fenestrated endografting. J Vasc Surg 2020;8:S0741-5214(20)30481-X. http://doi.org/10.1016/j.jvs.2020.02.051

9. Schwein A, Chinnadurai P, Behler G, Lumsden AB, Bismuth J, Bechara CF. Computed tomography angiography-fluoroscopy image fusion allows visceral vessel cannulation without angiography during fenestrated endovascular aneurysm repair. J Vasc Surg 2018l;68:2-11. http://doi.org/10.1016/j.jvs.2017.11.06.

10. Ahmad W, Gawenda M, Brunkwall S, Shahverdyan R, Brunkwall JS. Endovascular Aortoiliac Aneurysm Repair with Fenestrated Stent Graft and Iliac Side Branch Using Image Fusion without Iodinated Contrast Medium. Ann Vasc Surg 2016;33:231.e5-9. http://doi.org/10.1016/j.avsg.2015.11.031.

11. Vento V, Soler R, Fabre D, Gavit L, Majus E, Brenot P, et al. Optimizing imaging and reducing radiation exposure during complex aortic endovascular procedures. J Cardiovasc Surg (Torino) 2019;60:41-53. http://doi.org/10.23736/S0021-9509.18.10673-2.

12. Teraa M, Hazenberg CE, Houben IB, Trimarchi S, van Herwaarden JA. Important issues regarding planning and sizing for emergent TEVAR. J Cardiovasc Surg (Torino) 2020;23. http://doi.org/10.23736/S0021-9509.20.11571-4.

13. Belkin N, Jackson BM, Foley PJ, Damrauer SM, Kalapatapu V, Golden MA, et al. The use of intravascular ultrasound in the treatment of type B aortic dissection with thoracic endovascular aneurysm repair is associated with improved long-term survival. J Vasc Surg 2020;72:490-7. http://doi.org/10.1016/j.jvs.2019.

14. Tenorio ER, Oderich GS, Sandri GA, Ozbek P, Kärkkäinen JM, Vrtiska T, et al. Prospective nonrandomized study to evaluate cone beam computed tomography for technical assessment of standard and complex endovascular aortic repair. J Vasc Surg. 2020;71:1982-93.e5. http://doi.org/10.1016/j.jvs.2019.07.080.

15. Ierardi AM, Pesapane F, Rivolta N, Fumarola EM, Angileri SA, Piacentino F, et al.Type 2 endoleaks in endovascular aortic repair: cone beam CT and automatic vessel detection to guide the embolization. Acta Radiol 2018;59:681-687. http://doi.org/10.1177/0284185117729184.