

Original article

Low-cost digital tool kit for planning and sizing with 3D printing of abdominal aortic aneurysms for endovascular aortic repair: A Latinoamerican experience



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ABSTRACT

Introduction and objectives: 3D printing technology has recently been used to improve diagnosis and treatment of complex surgical cardiovascular diseases. This technology allows better appreciation of complex 3D anatomical and pathological conditions. The aim of the present study is to show a Latin American experience with a low-cost digital toolkit for planning and sizing with 3D printing of abdominal aortic aneurysms (AAA) for endovascular aortic repair (EVAR) and preoperative simulation, combining 2D and 3D technologies.

Methods: Prospective descriptive study. All patients that underwent EVAR between January and May 2021 were included. The EVAR procedures were planned using the low-cost digital tool kit with 3D printing. **Results:** The 3D printed models had fair transparency, absence of flexibility and no discrepancy between the computer-aided design. The models allowed external inspection but not the insertion of stent grafts due to the lack of lumen. The model had lower cost (25 USD per model), shorter manufacturing time (22 h 31 min), and an acceptable level of accuracy (2.61% error) compared to other methods.

Discussion: Using low-cost digital tool kits for planning and sizing with 3D printing, produces a robust physical model of a patient-specific AAA to aid endovascular aneurysm repair education and planning in a timely and cost-effective manner.

Conclusions: Overall, with the levels of transparency and flexibility provided by the 3D printed part, the patient-specific AAA model could potentially be used for surgical planning for individual patients but not for surgeons practicing endovascular aneurysm repair stent graft.

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Kit de herramientas digitales de bajo coste para la planificación y el dimensionamiento con impresión 3D de aneurismas aórticos abdominales para la reparación aórtica endovascular: una experiencia latinoamericana

RESUMEN

Introducción y objetivos: La tecnología de impresión 3D se ha utilizado recientemente para mejorar el diagnóstico y el tratamiento de enfermedades quirúrgicas cardiovasculares complejas. El objetivo del presente estudio es mostrar una experiencia latinoamericana con un kit de herramientas digitales de bajo coste para la planificación y el dimensionamiento con impresión 3D de aneurismas aórticos abdominales (AAA) para la reparación aórtica endovascular (RAE) y la simulación preoperatoria, combinando las tecnologías 2D y 3D.

Métodos: Estudio descriptivo prospectivo que incluye a los pacientes llevados a RAE durante el período comprendido entre enero y mayo del 2021. Todos los procedimientos de RAE de los pacientes se planificaron utilizando el kit de herramientas digitales de bajo coste para la planificación y el dimensionamiento con impresión 3D.

Resultados: El modelo tenía una transparencia justa, que permitía su inspección externa, pero no permitía la inserción de injertos de stent, y una flexibilidad nula con una discrepancia general entre el diseño asistido por computadora. El modelo tenía un costo menor (25 USD por modelo), un tiempo de fabricación más corto (22 h y 31 min) y un nivel de precisión aceptable (2,61% de error) en comparación con otros métodos.

Palabras clave:

Impresión 3D

Modelaje 3D

Aneurisma aórtico abdominal

Reparación endovascular aórtica

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Discusión: El uso de kits de herramientas digitales de bajo coste para la planificación y el dimensionamiento con impresión 3D, permite producir un modelo físico robusto de un AAA específico de un paciente para ayudar a la educación y la planificación de la reparación endovascular del aneurisma de una manera rentable y en tiempo.

Conclusiones: En general, con los niveles de transparencia y flexibilidad proporcionados por la pieza impresa en 3D, el modelo de AAA específico para el paciente podría utilizarse potencialmente para la planificación quirúrgica de pacientes individuales, pero no para los cirujanos que practican la reparación endovascular de aneurismas con endoprótesis.

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Introduction

The conventional way to perform the preoperative planning for endovascular aortic repair (EVAR) of an abdominal aortic aneurysms (AAA) is based on two dimensional (2D) reconstructions of the Computerized Tomography Angiography (CTA) images, and centerline based dimension measurements and three dimensional (3D) reconstructions of the 2D images.^{1–3} Planning of treatment for patients with Abdominal Aortic Aneurysms (AAA) needs the measure of various diameters, lengths and angles to choose the most ideal device for each specific patient. This process requires a detailed preoperative knowledge of the patient's aortic anatomy.⁴ An error in the preoperative planning in the EVAR may lead to misalignment, insufficient overlap, endoleaks, stent graft migration, limb occlusions, ruptures, or visceral malperfusion.⁵ Software packages are available for preoperative EVAR planning. These programs allow the surgeon an excellent precision of planning in most AAA cases in 2D and 3D.⁶ Nevertheless, in some AAA with short necks, severe juxta renal angulation, and proximity of visceral branches, the real dimensions are very difficult to understand for the vast majority of surgeons.⁷

In 2014, Hoffman et al.⁷ developed an accurate and rapid solid 3D aorta model using freely available software programs, and an accurate 3D printer. These solid models allowed palpation and manual handling and visual inspection for a better appreciation of visceral branches, complex AAA necks and simulation of the EVAR procedure.⁷ The color of the 3D model added a plus for the aortic anatomy comprehension, even for experienced surgeons. He concluded that 3D printing and modeling and outer shell fabrication for preoperative simulation are helpful in EVAR planning of complex AAA.⁷

The 3D printing technology has recently been used to improve diagnosis and treatment of complex surgical cardiovascular diseases. This technology allows better appreciation of complex 3D anatomic and pathologic conditions. In vascular surgery 3D models of aneurysms have been industrially produced from CTA images for the stent design and to train physicians and by EVAR manufacturing companies.^{7–10} Therefore, the aim of the present study is to show a Latinoamerican experience with a low-cost digital toolkit for planning and sizing with 3D printing of AAA for EVAR and preoperative simulation, combining the 2D and the 3D technologies.

Methods

We performed a prospective descriptive study, including patients taken to EVAR during the period between January and May of 2021. All patients EVAR procedures were planned using the low-cost digital tool kit for planning and sizing with 3D printing.

The CT scanning of the aorta was performed from the thoracic arch to below the common iliac arteries bifurcation (Aquilion One, Toshiba Medical Systems Ltd., UK). The slice thickness was 0.5 mm, with a pixel size of 0.625 mm. The process for segmentation and reconstruction of the patient-specific AAA CT scan data has been

described in detail previously by Conlisk et al.¹¹ Briefly, segmentation and reconstruction were carried out in commercial software (3D Slicer, BWH, US) using manual and semi-automatic thresholding tools, volume preserving smoothing (to remove scanning artifacts) and meshing operations were then performed in 3-matic (BWH). Finally, 3D meshes were exported in the printer compatible computer aided design (CAD) STL format. The chosen STL file was repaired to remove potential gaps in the geometry and to ensure smooth surfacing before 3D printing. The STL file was then transferred to the slicing software Cura (version 2.5, Ultimaker, Geldermalsen, Netherlands) for 3D printing. This software was used to automatically slice the file into suitable layers for 3D printing with the Ultimaker 3 3D printer. Print bed temperature was set as 40 °C in Cura 2.5 to ensure material adhesion to the print bed, while not exceeding the temperature limit where warping occurs (a phenomenon where the geometry closest to the print bed distorts due to an excessive print bed temperature being used). PVA support was required for the overhanging geometry of the AAA and so the printer's second extruder was primed for support structures with a brimmed adhesion layer between the model and the build plate for ease of removal with a spatula. The PVA printing parameters were fixed to the default recommended settings given in Cura 2.5.¹⁰

Data was collected from the patients' electronic medical records. The study did not present any biological, ethical or social risk to the participant patients. The medical ethics committee of the Hospital Militar Central approved the study.

3D printer

The Ultimaker 3 FDM 3D printer was used (Create Education Limited, UK). It has the capability for a minimum thickness layer of 20 µm, dual extrusion to utilize a second extruder for water-soluble support structure printing, and automatic build-plate leveling.¹⁰

Materials

Thermoplastic polyurethane (TPU) filament, manufactured by Ninjatek, called Ninjatek Cheetah Water (USA), and polyvinyl alcohol (PVA) filament, manufactured by Ultimaker, were purchased from Create Education Limited, UK.¹⁰

Results

During the study period, 4 patients underwent EVAR procedures (Table 1). Only one 3D printed model was performed per EVAR procedure. EVAR procedure features are described in Table 1. The 3D printed models had fair transparency, absence of flexibility and no discrepancy between the computer aided design. The models allowed external inspection of it but not the insertion of stent grafts due to the lack of lumen. The software used in the study doesn't allow to create a vascular lumen in the 3D printed model. This is a limitation of our 3D printed models due to not allowing the residents and fellows to perform previous EVAR simulation. The

Table 1
EVAR procedures features.

Procedure number	Gender	Age (years)	Aneurysm type	Aneurysm size (mm)	EVAR procedure type	Surgical time (minutes)	Complications
1	Male	62	Suprarrenal	61	Custom Made EVAR	251	No
2	Female	78	Infrarrenal	56	EVAR	114	No
3	Male	59	Yuxtarrrenal	67	Fenestrated EVAR	192	No
4	Male	73	Infrarrenal	59	EVAR	125	No

**Fig. 1.** 3D modeling printing of abdominal aorta and branches.**Fig. 2.** Example of 3D printing of giant abdominal aorta model.

model had lower cost (25 USD per model), shorter manufacturing time (22 h 31 min) and an acceptable level of accuracy (2.61% error) compared to other methods (Figs. 1 and 2).

Discussion

Using our low-cost digital tool kit for planning and sizing with 3D printing, we aimed to produce a robust physical model of a patient-specific AAA to aid endovascular aneurysm repair education and planning in a time and cost-effective manner. There are issues concerning surgical training and planning in EVAR. The EVAR approach has potential complications including migration of the graft and endoleaks. Options for surgical training and planning of EVAR include the use of virtual reality and experimental systems based on realistic models of AAA.^{12–15} Manufacturing techniques of AAA physical models are divided between casting techniques and 3D printing. Casting of aneurysm patterns is the creation of geometrically accurate models from transparent silicone rubbers. However, the time of manufacture has been an average of 2 weeks. The cost of this technique is around 200 and 1000 USD per model, due to requiring two sets of molds, for outer and inner geometry, and material waste. In this study the mean cost of each physical model was only 25 USD with an average time of manufacture of 22 h. Since 2000s, aneurysm models have been manufactured using rapid prototyping and 3D printing in a one-step process, like in our series, in which the final model is produced directly from 3D printing but in some cases a 2 or 3 step process may be required involving manufacture of a mold from the solid 3D printed core.^{7,9,10}

Low-cost AAA models have been accurately 3D printed using opaque and rigid thermoplastics such as polylactic acid (PLA). The main issue of 3D printed accurate AAA models is that these have

involved the use of expensive 3D printers such as Stratasys printers (£70,000) with Polyjet technology.¹⁰ Physical models of AAA have been manufactured for a variety of scientific purposes; inclusion in experimental flow systems to study flow patterns and pressures, for laboratory investigations of migration of stent grafts, and in experimental systems for simulation of interventional procedures. This high cost leads to a restriction in widespread clinical application in repetitive processes such as EVAR planning and surgical training.^{10,12,15} In this study we demonstrated the possibility of producing an accurate, semi-transparent patient-specific AAA model using a low-cost FDM machine. The CT scanning typically takes approximately 15 min, the total processing and manufacturing procedure could feasibly be done in less than 24 h as we showed in our cohort.

On the other hand, it is vital to know that while printing temperature and infill percentage only alter the geometry of the model compared to the CAD model by a range of around 2%, increasing printing speed has a more adverse effect on accuracy.¹⁰ This is why in our study we do not recommend a printing time of less than 20 h to avoid an increase in dimensional error. The ideal print speed is

30 mm/s to maintain the model error range less than 2%.^{10,13,14} All the STL files accessed for this study had the geometrical data for the iliac arteries. This feature allows our models to plan more complex AAA geometries, such as AAAs that extend into the iliac arteries or those with short neck distance to the renal arteries, as most AAAs are not infrarenal compared to other series like the reported by Chung et al.¹⁰ with the limitation of difficult anatomies below the aorto iliac bifurcation.¹⁰

The principal problem with our 3D printed AAA model was that it can not sustain the endovascular aneurysm repair testing. This issue is due to the absence of lumen that does not allow the possibility to perform previous EVAR simulation to probe the different abdominal aortic endografts and identify the best option to each patient aortic anatomy. The next step of this project is to finance the purchase of software that allows the creation and printing of 3d aortic models with lumen. The 3D printed AAA model had lower cost (25 USD per model), shorter manufacturing time (22 h 31 min) and higher accuracy (~2.5% error) compared to other methods reported in literature.¹⁶ The cost per model was higher than the opaque, rigid 3D printed AAA model (6 USD per model) reported by Bangeas et al.¹⁷ The main barriers to more widespread clinical adoption of 3D printing are the high costs of the art 3D printing systems (81,000 USD) but this is changing with the new low cost hardware development as the Ultimaker 3 printer that costs approximately 3850 USD.¹⁷

This study had some limitations. The final AAA model was only semi-transparent without hollows that did not allow the testing of AAA endografts, and had poor transparency compared to silicone rubbers with optically clear transparency. A stent graft could not be placed inside the model to give a fair evaluation of effectiveness. Investigations into using alternative materials which have higher transparency and with material with higher compliance, would improve the model drastically.

Conclusions

Overall, with the levels of transparency and flexibility provided by the 3D printed part, the patient-specific AAA model could potentially be used for surgical planning for individual patients but not for surgeons practicing endovascular aneurysm repair stent graft. Conversely, due to lack of similarity to aortic properties, the 3D printed AAA model would not be useful for endovascular aneurysm repair simulation, peak wall stress or fluid flow testing.

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Conflict of interest

The authors declare that they have no conflicts of interest.

References

1. Coles-Black J, Barber T, Bolton D, Chuen J. A systematic review of three-dimensional printed template-assisted physician-modified stent grafts for fenestrated endovascular aneurysm repair. *J Vasc Surg.* 2021;74: 296–306.e1.
2. Branzan D, Geisler A, Grunert R, Steiner S, Bausback Y, Gockel I, et al. The influence of 3D printed aortic models on the evolution of physician modified stent grafts for the urgent treatment of thoraco-abdominal and pararenal aortic pathologies. *Eur J Vasc Endovasc Surg.* 2021;61:407–12.
3. Tong YH, Yu T, Zhou MJ, Liu C, Zhou M, Jiang Q, et al. Use of 3D printing to guide creation of fenestrations in physician-modified stent-grafts for treatment of thoracoabdominal aortic disease. *J Endovasc Ther.* 2020;27:385–93.
4. Kudo T, Kuratani T, Shimamura K, Sawa Y. Early and midterm results of thoracic endovascular aortic repair using a branched endograft for aortic arch pathologies: a retrospective single-center study. *JTCVS Tech.* 2020;4:17–25.
5. Coles-Black J, Bolton D, Robinson D, Chuen J. Utility of 3D printed abdominal aortic aneurysm phantoms: a systematic review. *ANZ J Surg.* 2021. Online ahead of print.
6. Edsfeldt A, Sonesson B, Rosén H, Petri MH, Hongku K, Resch T, et al. Validation of a new method for 2D fusion imaging registration in a system prepared only for 3D. *J Endovasc Ther.* 2020;27:468–72.
7. Hoffman A, Nitecki S, Engel A, Karram T, Leiderman M, Si-On E, et al. In house enhanced 3D printing of complex AAA for EVAR treatment planning and preoperative simulation. *J Cardiovasc Dis Diagn.* 2014;2:181.
8. Vatakencherry G, Molloy C, Sheth N, Liao M, Ken Lam C. Percutaneous access planning, techniques and considerations for endovascular aortic repair (EVAR). *Cardiovasc Diagn Ther.* 2018;8(S-1):S184–90.
9. Kicska G, Litt H. Preprocedural planning for endovascular stent-graft placement. *Semin Intervent Radiol.* 2009;26:44–55.
10. Chung M, Radacsi N, Robert C, McCarthy ED, Callanan A, Conlisk N, et al. On the optimization of low-cost FDM 3D printers for accurate replication of patient-specific abdominal aortic aneurysm geometry. *3D Print Med.* 2018;4:2.
11. Conlisk N, Geers AJ, McBride OMB, Newby DE, Hoskins PR. Patient-specific modelling of abdominal aortic aneurysms: the influence of wall thickness on predicted clinical outcomes. *Med Eng Phys.* 2016;38:526–37.
12. See KWM, Chui KH, Chan WH, Wong KC, Chan YC. Evidence for endovascular simulation training: a systematic review. *Eur J Vasc Endovasc Surg.* 2016;51:441–51.
13. Saratzis A, Calderbank T, Sidloff D, Bown MJ, Davies RS. Role of simulation in endovascular aneurysm repair (EVAR) training: a preliminary study. *Eur J Vasc Endovasc Surg.* 2017;53:193–8.
14. Mafeld S, Nesbitt C, McCaslin J, Bagnall A, Davey P, Bose P, et al. Three-dimensional (3D) printed endovascular simulation models: a feasibility study. *Ann Transl Med.* 2017;5:42.
15. Torres IO, De Luccia N. A simulator for training in endovascular aneurysm repair: the use of three dimensional printers. *Eur J Vasc Endovasc Surg.* 2017;54:247–53.
16. Kono K, Shintani A, Okada H, Terada T. Preoperative simulations of endovascular treatment for a cerebral aneurysm using a patient-specific vascular silicone model. *Neurol Med Chir (Tokyo).* 2013;53:347–51.
17. Bangeas P, Voulalas G, Ktenidis K. Rapid prototyping in aortic surgery. *Interact Cardiovasc Thorac Surg.* 2016;22:513–4.