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Evaluating compliance in three-dimensional-printed polymeric vascular grafts compared to human arteries and commercial grafts in a mock circulation loop compliance in three-dimensional-printed polymeric vascular grafts

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ABSTRACT

Compliance mismatch between native arteries and prosthetic grafts contribute to complications such as neointimal hyperplasia and pseudoaneurysms, leading to reduced graft patency. Three-dimensional (3D) printing offers a promising solution by flexibly customizing mechanical properties using elastic polymers. This study investigates whether 3D-printed polymeric grafts can better replicate native arterial compliance compared with commercial prosthetic grafts. We conducted compliance tests on human aortoiliac arteries, polytetrafluoroethylene (PTFE) grafts, Dacron grafts, and 3D-printed arteries with BioMed Elastic Resin within a mock circulation loop. All samples shared controlled geometry and were tested under the same physiological flow conditions. Pressure waveforms and key hemodynamic parameters were recorded and analyzed. The 3D-printed graft demonstrated a compliance of 0.49 cm^3/mmHg, more closely matching the human artery than PTFE (0.38 cm^3/mmHg) and Dacron (0.45 cm^3/mmHg). Its mean arterial pressure (82 ± 0.6 mmHg) and peak pressure (40 ± 0.7 mmHg) in the flow loop also aligned more closely with the native artery compared with conventional grafts. Standard prosthetic graft materials have remained relatively static, whereas there has been immense advancement in new polymer technology. These polymers can match the compliance of native vessels, theoretically reducing complications associated with traditional grafts, and future work should investigate their biocompatibility, durability, and clinical feasibility. (JVS—Vascular Science 2025;6:100291.)

Keywords: Bypass graft; Compliance; Flow loop; Biomaterials

Improving the longevity and performance of prosthetic vascular grafts has remained a key challenge in cardiovascular research for decades. A major factor limiting success is the compliance mismatch between prosthetic grafts and native vessels. When grafts fail to mimic native arterial mechanics, they disrupt hemodynamics at the anastomosis, leading to neointimal hyperplasia and graft occlusion.[1,2] This mismatch alters wall shear stress, promoting disturbed flow and particle trapping near the graft interface.[1,2] Over time, the resulting flow stagnation contributes to thrombosis and accelerates neointimal thickening, ultimately reducing graft patency.[3] Furthermore, the increased suture line stress caused by compliance mismatch can lead to the development of pseudoaneurysms, small bulges at the site of the surgical connection.[4] Historically, the materials used for vascular grafts, such as Dacron and polytetrafluoroethylene (PTFE), have remained largely unchanged since their introduction. Although these materials offer durability, their mechanical properties differ significantly from those of native arteries, contributing to the complications associated with compliance mismatch. Despite the critical need for improvement, progress has been slow in the development of new graft materials that can better replicate the elasticity of native vessels.[5-9]

Utilizing three-dimensional (3D) printing to construct vascular grafts with customized elastic polymers and preconstructed branches allows for a significant enhancement in matching the mechanical properties of native arteries.[10] This customization potential of 3D printing could lead to notable improvements in graft integration, reducing complications associated with compliance mismatch and thus improving clinical outcomes in vascular surgery. Recent advances in 3D

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printing technology and the development of novel polymers have opened exciting possibilities for addressing this long-standing issue.[11-13] Furthermore, the introduction of innovative polymeric materials, specifically designed for biocompatibility and mechanical resilience, has shown promise in preliminary studies. These materials aim to replicate the elastic properties of arterial walls, potentially reducing common complications such as compliance mismatch, anastomotic neointimal hyperplasia, and the formation of anastomotic pseudoaneurysms. This evolution from conventional prosthetic materials towards solutions that more closely resemble biological tissues in vascular surgery may pave the way for improved patient outcomes.

This study seeks to build on these advances by evaluating the compliance of 3D-printed vascular grafts made from polymeric materials in comparison to human arteries and traditional Dacron and PTFE grafts. Using a mock circulation loop developed in a previous study,[14] which simulates the pulsatile flow and pressure conditions of the human circulatory system, we aimed to determine whether 3D-printed grafts can offer improved compliance matching, ultimately reducing the risk of complications associated with compliance mismatch.

MATERIALS AND METHODS

The following sections outline the design of the experiment and the fabrication of the aortic models used in the experiments.

Mock circulation loop setup. A mock circulation loop (MCL) was designed to replicate human arterial flow conditions, providing a controlled environment for studying hemodynamics.[14] The schematic diagram and corresponding benchtop setup of the MCL are illustrated in Fig 1, which also includes an image of four aortic models: (1) human artery; (2) PTFE graft; (3) Dacron graft; and (4) 3D-printed polymeric artery.

The MCL consists of a reservoir, a pulsatile blood pump (Harvard Apparatus, Model 1434), a test section housing the tested arterial system, Windkessel chambers, and resistance valves. The pulsatile blood pump allows for continuous adjustment of the heart rate (HR), stroke volume, and the systole-to-diastole phase ratio. Windkessel chambers, cylindrical glass bottles measuring 10 cm in diameter and 20 cm in height, model the Windkessel effect. One Windkessel chamber is mounted upstream of the test section's inlet to mimic upper-body systemic compliance. Additionally, each arterial outlet is equipped with one Windkessel chamber and two resistance valves to simulate vessel compliance and proximal/distal flow resistances, respectively. This setup is consistent with the three-element Windkessel model used in our previous computation study[15] using image-based computational hemodynamics.[16-18] All components of the system are connected using flexible silicone tubing with an inner diameter of 0.5 inches. We utilized a water-glycerin mixture to simulate the blood's viscosity and density more accurately. The mixture consists of 45% glycerin by volume, resulting in a viscosity of approximately 3.0 cP and a density of 1.1 g/mL, closely approximating that of human blood.[19] The Reynolds number, based on the average flow velocity and hydraulic diameter of our system, was found to be approximately 25,220. The Womersley number was calculated to be around 13.2. More details about the MCL settings can be found in our previous study.[14]

Aortic models. The study involved the evaluation of four types of vascular materials: human aortoiliac arteries, PTFE grafts, Dacron grafts, and 3D-printed arteries. Other types of materials were initially investigated, but the forementioned materials gave us the most robust comparison of current potential grafts without extensively analyzing materials with lower compliance.

The human aortoiliac segments were generously provided by Cryolife, Inc, served as the control, and had an inner diameter of 12.5 mm, a wall thickness of approximately 0.3 mm, and a total length of 150 mm. They are the same arteries utilized in human revascularization procedures. The experiment was conducted in an Indiana University-approved biolab with proper tissue disposal per protocols. In the vendor's preparation, the cells and antigens are removed while preserving the collagen matrix. The commercial prosthetic grafts used in this study are PTFE and Dacron grafts, and a 3D-printed aortic model, all of which share identical geometric parameters: an inner diameter of 12.7 mm, an aortic segment length of 120 mm, and bifurcation segment lengths of 70 mm each. However, they differ in wall thickness—PTFE grafts have a wall thickness of 0.25 mm, Dacron grafts are slightly thinner at 0.2 mm, and the 3D-printed aortic model has a wall thickness of 0.4 mm. This 0.4 mm thickness for 3D-printed aortic model was selected based on a preliminary static inflation test comparing printed models with wall thicknesses ranging from 0.4 mm to 1.0 mm, and the 0.4 mm model demonstrated the highest compliance among the tested variants.

The morphology of the 3D-printed aortic models was designed to replicate the geometries of the PTFE and Dacron grafts. Detailed geometric information for the PTFE graft was captured and reproduced using computer-aided design software, which generates a Standard Tessellation Language file, a commonly used format for 3D printing. Form 3 Stereolithography (SLA) 3D printer (Formlabs) is renowned for its high precision and excellent surface finish, which are critical for creating detailed and dimensionally accurate models that mimic the complex structures of native tissues. The Form 3 SLA 3D printer allows printing models inside a 15 cm ×

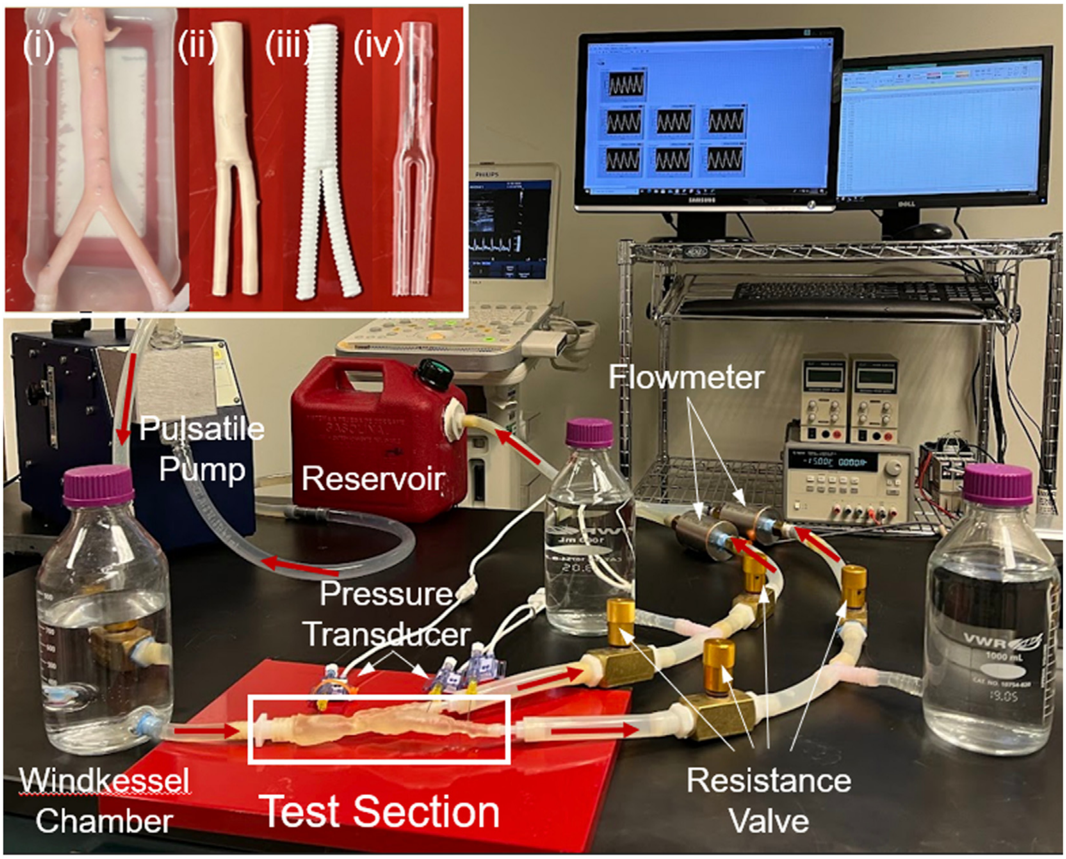

Fig 1. Benchtop setup of mock circulation loop (MCL) to measure blood pressure waveforms in aortoiliac artery systems: (i) human artery; (ii) polytetrafluoroethylene (PTFE) graft; (iii) Dacron graft; and (iv) three-dimensional (3D)-printed polymeric artery.

Table I. Mechanical properties of the human aorta, Dacron graft, polytetrafluoroethylene (*PTFE*) graft and the five polymer resins used for three-dimensional (3D)-printed aortic models

	PTFE	Dacron	Human artery	Clear resin	Flexible resin	Elastic resin	BioMed flexible resin	BioMed elastic resin
Tensile strength, MPa	14	170	1.4-11	51	8.9	3.4	7.2	2.3
Young's modules, MPa	500	14,000	0.3-1.5	/	4.5	1.7	4.5	1.3

15 cm × 20 cm space. The ease of 3D printing varies among the resin types and is influenced by both the resin properties and the model design. Although the overall printing process remains consistent across all resins using the Formlabs SLA printer, the printing software automatically adjusts certain parameters—such as the number and size of support touchpoints and total printing time—based on the selected material to optimize print quality and reliability. Generally, more rigid resins allow for quicker printing times, ranging from 2 to 6 hours per model, depending on the complexity and orientation of the model. For an optimal material selection, we evaluated five polymer resins (Formlabs): Clear Resin, Flexible Resin, Elastic Resin, BioMed Flexible Resin, and BioMed Elastic Resin. Detailed mechanical properties, such as tensile strength and Young's modulus, are presented in Table I. Among all materails, BioMed Elastic Resin exhibited mechanical properties most similar to those of the native human artery. Compared with both commercial grafts (PTFE and Dacron) and other 3D-printed resins (eg, Clear Resin and Flexible Resin), BioMed Elastic Resin demonstrated superior compliance and a closer match to the native vessel's mechanical behavior. Thus, BioMed Elastic Resin was selected for further testing due to its superior mechanical properties and compliance.

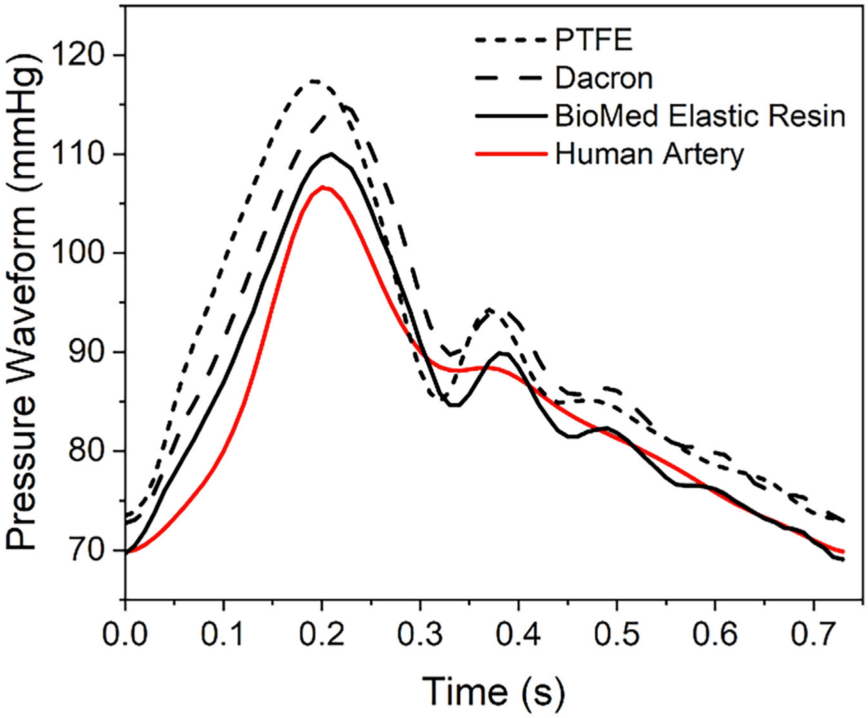

Fig 2. Comparisons of blood pressure measurements in four aortoiliac arteries: polytetrafluoroethylene (PTFE) graft, Dacron graft, three-dimensional (3D)-printed artery using BioMed Elastic Resin (0.4 mm), and human artery.

Experimental procedures. The pressure waveforms and hemodynamic characteristic measurements were conducted by exposing the different arterial samples to pulsatile flow within the mock circulation loop. To address the movement of flexible phantoms due to pulsatility, we utilized a mounting technique involving custom-designed adaptors for secure connections between the artery and flow tubing. Medical-grade tape ensures the artery or graft remains firmly in place. For each material, five repeated measurements were taken under a constant upstream waveform setting, HR at 80 bpm, stroke volume at 25 mL, and systole-to-diastole ratio 25/75, to ensure accuracy. Key hemodynamic parameters, including HR, systolic pressure, diastolic pressure, pulse pressure (PP), and mean arterial pressure (MAP), were recorded for each sample during the test runs. This approach allowed us to isolate and measure the compliance as the independent variable, directly assessing how the different materials influenced the hemodynamic responses. By maintaining constant upstream conditions and only varying the aortic models, we ensured that any observed differences in compliance and other hemodynamic parameters were attributable solely to the material properties of the models, thereby providing a clear understanding of how material compliance affects vascular dynamics. The pressure waveforms generated for each material were analyzed to determine compliance, calculated as the change in volume per unit change in pressure (cm^3/mmHg). These results were compared to assess how closely the compliance of the 3D-printed arteries matched that of the human artery and the PTFE graft. Statistical analysis was performed to determine the significance of the compliance differences among the materials.

Compliance estimation. Compliance can be estimated using the decay time method (DTM),[20] which involves analyzing the pressure decay curve during diastole. When the exact start of diastole is unclear or if the pressure decay phase does not start precisely at a known time (eg, due to measurement limitations or physiological variability), we can generalize the diastolic pressure decay equation with an arbitrary reference time and include an offset pressure. This leads to a more flexible exponential decay form:

$$P(t) = P_0 \cdot e^{-\frac{t}{\tau}} + P_\infty \tag{1}$$

where $P(t)$ is the pressure over time; P_0 is the initial amplitude of the decaying exponential (not necessarily equal to systolic or diastolic pressure); P_∞ is the residual pressure at infinite time and is often referred to as the zero-flow pressure or venous pressure offset. This model acknowledges that arterial pressure does not decay fully to zero but levels off toward a physiological baseline pressure, making it more accurate and practical in real-world measurements. During diastole, by fitting an

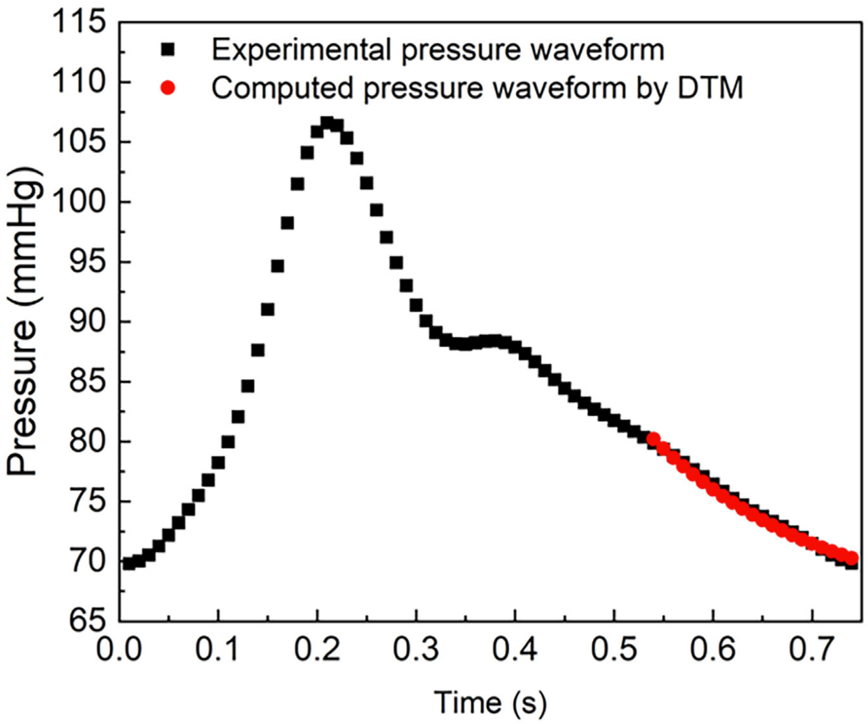

Fig 3. Pressure waveform fitting to diastolic phase using decay time method (*DTM*).

exponential curve to the pressure decay (as shown in Fig 2), the time constant (τ) was extracted, and compliance was calculated using the relationship:

$$C = \frac{\tau}{R} \tag{2}$$

where C is the compliance and R is the resistance in the system.

RESULTS

As shown in Fig 2, the pressure waveforms highlight the ability of the BioMed Elastic Resin to better mimic the compliance of native arteries compared with conventional materials. Although the BioMed Elastic Resin model still exhibits slightly stiffer behavior than the human artery, as evidenced by its sharper pressure drop during diastole, it outperforms the PTFE and Dacron grafts, which have markedly higher peak pressures and a faster pressure decay.

In addition to analyzing the pressure waveforms, we utilized the DTM to estimate the compliance of each model based on their pressure decay during the diastolic phase. As shown in Fig 3, the experimental pressure waveforms fit with an exponential decay curve, allowing us to extract the τ and compute the compliance for each model. This method further validated our findings from the pressure waveform analysis, confirming that the BioMed Elastic Resin exhibits higher compliance compared with the PTFE and Dacron grafts, though it still falls short of matching the native human artery. The compliance values derived from DTM are summarized in Table II.

Other hemodynamic characteristics are summarized for all materials in Table II, with respective errors. The data reveal that the BioMed Elastic Resin model demonstrates a compliance value of 0.49 cm^3/mmHg, which is higher than that of PTFE (0.38 cm^3/mmHg) and Dacron (0.45 cm^3/mmHg). Although BioMed Elastic Resin does not reach the compliance of a native human artery (0.64 cm^3/mmHg), it shows a notable improvement over the conventional graft materials. These compliance differences are inherently linked to the elastic properties of each material. Compliance, which describes the vessel's ability to expand under pressure, is strongly influenced by the material's elasticity—specifically its Young's modulus and tensile strength. Materials with lower stiffness tend to deform more under physiological pressures, resulting in higher compliance. Conversely, stiffer materials resist deformation, leading to lower compliance. This relationship underscores the importance of evaluating elasticity when selecting or developing graft materials intended to replicate native vessel behavior.

Additionally, the BioMed Elastic Resin model exhibits lower MAP and PP compared with PTFE and Dacron, indicating a more favorable hemodynamic performance. The MAP for the BioMed Elastic Resin was 82 ± 0.6 mmHg, which closely aligns with the human artery's 82 ± 0.4 mmHg, whereas PTFE and Dacron

Table II. Hemodynamic characteristics of four materials: polytetrafluoroethylene (*PTFE*) graft, Dacron graft, three-dimensional (3D)-printed artery using BioMed Elastic Resin (0.4 mm), and human artery

Material	Compliance, cm^3/mmHg	HR, BPM	SP, mmHg	DP, mmHg	PP, mmHg	MAP, mmHg
PTFE	0.38	83 ± 0.6	118 ± 0.3	73 ± 0.1	44 ± 0.4	88 ± 0.1
Dacron	0.45	83 ± 0.2	115 ± 0.4	73 ± 0.1	42 ± 0.5	87 ± 0.3
BioMed elastic resin	0.49	82 ± 0.6	109 ± 0.3	69 ± 0.4	40 ± 0.7	82 ± 0.6
Human artery	0.64	82 ± 0	106 ± 1.0	70 ± 0.1	36 ± 1.0	82 ± 0.4

DP, Diastolic pressure; *HR,* heart rate; *MAP,* mean arterial pressure; *PP,* pulse pressure; *SP,* systolic pressure.

displayed higher MAP of 88 ± 0.1 mmHg and 87 ± 0.3 mmHg, respectively. Similarly, the PP for BioMed Elastic Resin (40 ± 0.7 mmHg) was lower than that of PTFE (44 ± 0.4 mmHg) and Dacron (42 ± 0.5 mmHg), indicating that the BioMed Elastic Resin can better absorb pressure fluctuations, contributing to its more compliant behavior.

Together, the pressure waveform and hemodynamic data confirm that the BioMed Elastic Resin model demonstrates superior compliance compared with PTFE and Dacron grafts, approaching the performance of the native human artery. However, there is still room for further optimization, as the BioMed Elastic Resin remains slightly stiffer than the human artery.

DISCUSSION

This study compared the compliance and hemodynamic behavior of 3D-printed BioMed Elastic Resin aortic model with traditional prosthetic graft materials, PTFE and Dacron, as well as native human artery. The BioMed Elastic Resin demonstrated higher compliance than PTFE and Dacron grafts, approaching the performance of native arteries, as reflected in both the pressure waveforms and the hemodynamic data. Specifically, BioMed Elastic Resin exhibited more favorable MAP and PP, closely aligning with the values of native arteries, whereas PTFE and Dacron showed stiffer behavior.

The BioMed Elastic Resin aortic model displayed superior compliance compared with conventional prosthetic grafts, demonstrating the potential of these new polymer materials to mimic native arterial behavior. The ability to customize compliance through thickness adjustments may lead to improved graft patency, reduced neointima formation, and decreased pseudoaneurysm occurrence, offering significant advancements in vascular graft technology.

In addition to more closely matching human arterial compliance, further experimental work is needed. Future research should focus on investigating the biocompatibility, durability, and suturability of these materials in animal models to assess their clinical feasibility. Since this experimental study, new polymers have been developed, which may even more closely match the compliance of human arteries. These polymers should be tested.

CONCLUSIONS

This study highlights the promise of polymeric resin grafts to better match the compliance of human arteries. Future research should focus on investigating the biocompatibility, durability, and suturability of these materials in flow loops and animal models to assess their clinical feasibility. Expanding this work to include other polymer materials and exploring their real-world clinical applications will be essential for validating the findings of this preliminary study and moving towards the deployment of 3D-printed vascular grafts in clinical practice.

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DISCLOSURES

None.

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