Effects of Pulsatile Fatigue on In Situ Antegrade Fenestrated Polyester Stent Grafts Deployed in a Patient-Specific Phantom Model of Juxtarenal Aortic Aneurysm

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ABSTRACT

Purpose: To evaluate the effects of in situ fenestration on the fabric of stent grafts deployed in a patient-specific phantom of a juxtarenal abdominal aortic aneurysm.

Materials and Methods: Four patient-specific juxtarenal abdominal aortic aneurysm polyurethane models were created, and bifurcated Zenith (Cook, Inc, Bloomington, Indiana) and Endurant (Medtronic, Minneapolis, Minneapolis) endografts were deployed into the models, covering the renal arteries. Antegrade in situ fenestration was carried out with radiofrequency puncture followed by balloon dilation with either conventional or cutting balloons. Renal covered stents were deployed and flared. Specimens were mounted onto an accelerated fatigue tester for 40M cycles (1 patient life-year), and evaluated with microscopy, caliper measurements, and fabric counts.

Results: Cutting balloons resulted in more fabric fraying. None of the fenestrations grew beyond the targeted 6-mm diameter despite accelerated fatigue. Fluoroscopic images demonstrated a very prominent waist of the renal fenestration in the Cook device when a conventional balloon was used compared with a cutting balloon. The average fenestration diameter for the Cook device was only 3.1 mm with the conventional balloon compared with 4.8 mm with the cutting balloon. The average fenestration diameter for the Medtronic device was 3.8 mm with the conventional balloon compared with 5.1 mm with the cutting balloon. The fabric counts suggested crowding of yarns around the fenestrations with conventional balloons but less with cutting balloons.

Conclusions: This experimental work suggests that the size of in situ renal fenestrations does not expand beyond the target diameter despite cyclic fatigue. Although the small number of devices tested and selected aortorenal anatomy in this study may limit conclusions, textile analysis suggests that cutting balloons should be used for the Cook Zenith device, whereas conventional balloons should be used for the Medtronic Endurant device when performing in situ fenestration.

The technique of in situ fenestration of aortic stent grafts has been demonstrated to be feasible in antegrade (1–7) and retrograde (8–15) fashions. Although retrograde fenestration of thoracic stent grafts in the aortic arch is technically easier, juxtarenal abdominal aortic aneurysms are a more common disease (16) and would require

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application of antegrade fenestration if in situ techniques are used. The technical feasibility of antegrade fenestration has been demonstrated in animal models (3,6,7) and subsequent human case reports (1,2); however, the important question of fabric durability still needs to be evaluated. A few studies of acute fabric damage have been published (17,18), and a more long-term bench fatigue study has been performed on simple fabric samples (19). The present proof of concept study involves full bifurcated stent-graft devices deployed in a patient-specific phantom that underwent bilateral in situ fenestration to the renal arteries followed by accelerated pulsatile fatigue testing to represent 1 year of in vivo life (40 million cycles). This study also included the use of cutting balloons to address the previously identified problem of underdilation in the Cook Zenith device (Cook, Inc, Bloomington, Indiana) (19).

MATERIALS AND METHODS

A patient-specific three-dimensional model of an abdominal aortic aneurysm was created from the supraceliac aorta to the iliac bifurcations. Use of computed tomography imaging of an anonymous patient to create model phantoms was approved by the institutional ethics committee. The model was used as a mold to create four polyurethane optically opaque but radiolucent phantoms. The detailed technique of phantom processing and construction was reported previously (20). A custom-made apparatus was built to mount the branches and allow filling with saline and electrical grounding.

Into each phantom, a bifurcated commercial stent graft was deployed under fluoroscopy such that the covered portion was just below the superior mesenteric artery (**Fig 1a**) and both renal arteries were covered.

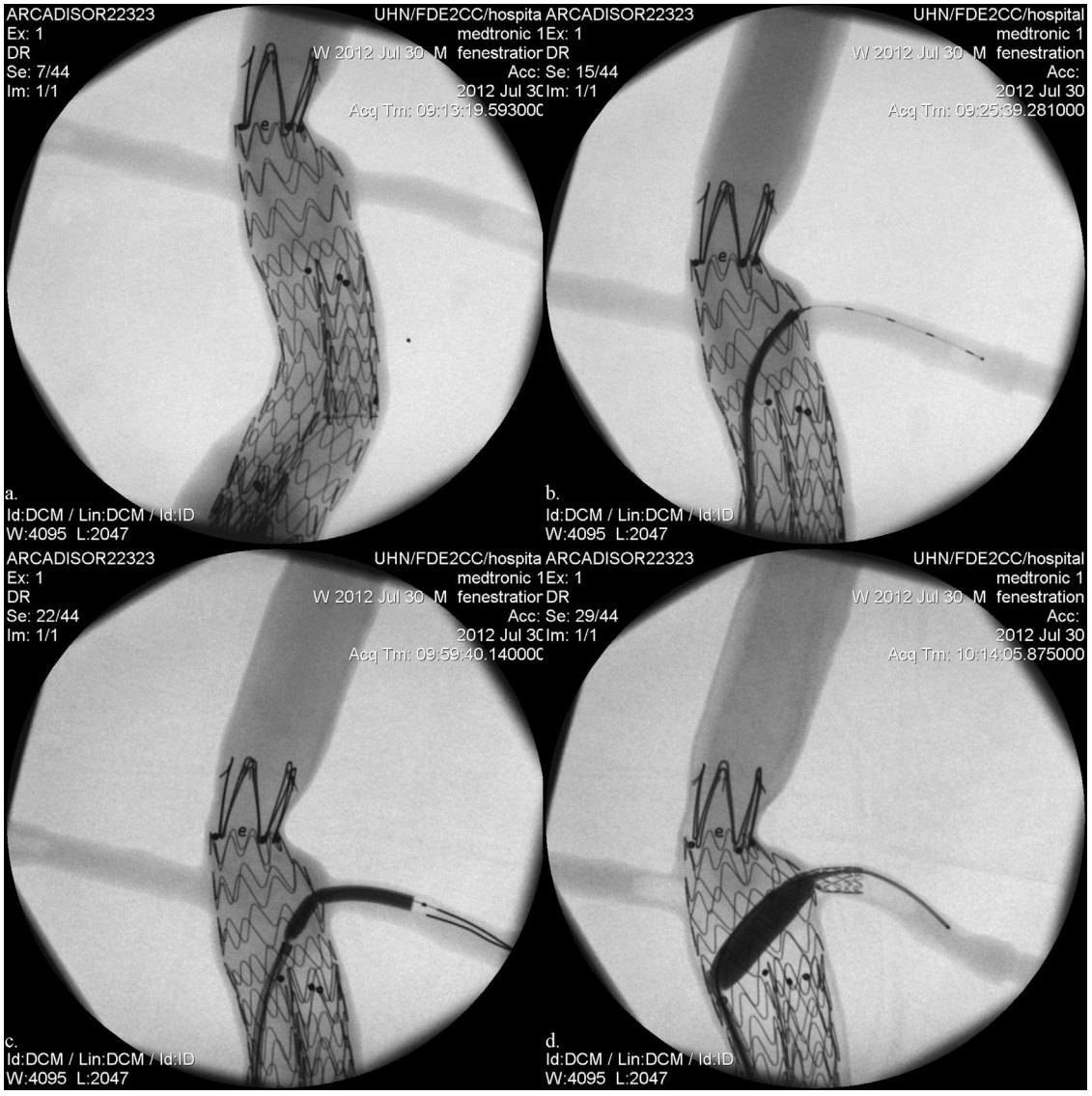

Figure 1. Fluoroscopic images show **(a)** an aortic stent graft deployed in a patient-specific phantom model such that the top of the fabric is above both renal arteries but below the superior mesenteric artery, **(b)** a radiofrequency wire advanced into the left renal artery after having punctured the graft fabric, **(c)** dilation of a graft fabric puncture with a 4-mm angioplasty balloon, and **(d)** flaring of a 6-mm covered stent using a 10-mm angioplasty balloon.

Bilateral iliac limb extensions were implanted to the common iliac arteries. The modular endograft system was either a stainless steel bifurcated endograft (Zenith) or a nitinol bifurcated endograft system (Endurant; Medtronic, Minneapolis, Minneapolis). Antegrade in situ fenestration was carried out under fluoroscopy using a straight-tipped 0.035-inch radiofrequency wire (PowerWire; Baylis Medical, Mississauga, Ontario, Canada) to puncture the graft from inside the main body out into each renal artery. A 7-Fr directional guiding sheath (Destination; Terumo Medical Corporation, Somerset, New Jersey) and various 5-F guiding catheters (eg, Beacon; Cook, Inc) were used to guide the wire puncture under fluoroscopy (**Fig 1b**). The catheter was advanced over the wire and used to exchange the radiofrequency wire for an 0.018-inch wire (V-18 ControlWire; Boston Scientific, Marlborough, Massachusetts). Balloon catheters were used to dilate the graft fabric, using either a 4-mm angioplasty balloon (Mustang; Boston Scientific) or a 4-mm cutting balloon (Flextome; Boston Scientific) inflated by a manometer (Sphere Inflation Device; Cook, Inc) to 10 atm (**Fig 1c**). The 0.018-inch wire was then exchanged for a 0.035-inch short-tip guide wire (Amplatz Super Stiff; Boston Scientific). A 6 mm × 22 mm balloon-expandable covered stent (Advanta V12; Atrium Medical, Hudson, New Hampshire) was deployed across the fenestration with balloon inflation to 10 atm, and the aortic end was flared with a 10-mm balloon (Mustang) inflated by hand (**Fig 1d**). Of the four specimens, one was a Cook Zenith with conventional balloons (GC1), one was a Cook Zenith with cutting balloons (GC2), one was a Medtronic Endurant with conventional balloons (GM1), and one was a Medtronic Endurant with cutting balloons (GM2).

The phantoms were then removed from the apparatus and mounted onto an accelerated pulsatile fatigue tester (EnduraTec; Bose Corp, Framingham, Massachusetts), filled with water at 37°C, and cycled with a pressure of 160/90 mmHg at 40–60 Hz for 40 million cycles to represent 1 year of patient life. The frequency at which the cyclic fatigue testing was conducted represented the maximum rate of testing, above which the experimental apparatus became unstable. The frequency of 50 Hz was previously found to be valid in cyclic fatigue studies of endovascular nitinol (21). At points determined beforehand of 0 cycles, 1 million cycles, 5 million cycles, 15 million cycles, and 40 million cycles, an endoscope was used to visually inspect for any overt dislodgment of renal stents during the fatigue process. The phantoms were removed after 40 million cycles and inspected. The Atrium Advanta V12 stents were carefully removed, and analysis of the fabric fenestration was performed. This analysis included caliper measurement of fenestration dimension, videomicroscopy of the fenestration edges with special attention to yarn ends, and fabric count. For the fabric count, high-resolution images of the graft fabric were taken, and the warp and weft yarn counts were taken over a distance of 2 mm, starting at 0.1 mm away from the fenestration edge. The counts were taken above, below, and to each side of the fenestration. Warp and weft yarn counts were also taken on unfenestrated areas of the fatigued specimens to serve as control data. The fabric count measurements were used and interpreted for comparative purposes rather than absolute quantitative values.

RESULTS

Acute Fenestration and Fatigue Process

Antegrade in situ fenestration was successful for all eight renal arteries in all four phantoms. There was a very prominent waist of the renal fenestration in the Cook Zenith device when a conventional balloon was used compared with a cutting balloon (**Fig 2a, b**). The difference was not as prominent with the Medtronic Endurant device because the conventional balloon was able to achieve a larger fenestration in this fabric (**Fig 2c, d**). Retrospective estimation of perforation angles was carried out by measuring the angle between the wire and the aortic stent graft at their junction at the fenestration and on intraoperative fluoroscopic images. The overall average angle was 73° (range, 62°–82°). The average for the left renal artery was 74° (range, 65°–86°), and the average for the right renal artery was 71° (range, 62°–80°). The average for Cook devices was 70° (range, 62°–76°), and the average for Medtronic devices was 74° (range, 65°–86°).

Inspections that were carried out by endoscopy during accelerated fatigue testing were negative for any renal stent dislodgment. **Figure 3** is a representative image from the medium-resolution endoscope that was used.

Analysis after Fatigue Testing

After 40 million cycles of pulsatile pressure, the devices were inspected visually and by microscope. As seen in **Figures 4a–d** and **Figure 5a–d**, use of the cutting balloon resulted in more frayed fibers, as opposed to more melted and fused fibers as seen in the conventional balloons. Overall, there appeared to be more fraying seen in the Medtronic fabric compared with the Cook fabric.

The caliper measurements of the fenestrations indicate that none of the fenestrations exceeded the designated balloon diameter of 6 mm. The average fenestration diameter for the Cook device was only 3.1 mm with the conventional balloon compared with 4.8 mm with the cutting balloon. The average fenestration diameter for the Medtronic device was 3.8 mm with the conventional balloon compared with 5.1 mm with the cutting balloon. The left renal fenestrations were slightly but consistently larger than the right renal fenestrations, suggesting that the angles of graft perforation may play a role in fenestration, as was suggested by Riga et al (18). The fabric count is a standard measure of the fabric yarn density in the longitudinal (warp) and circumferential

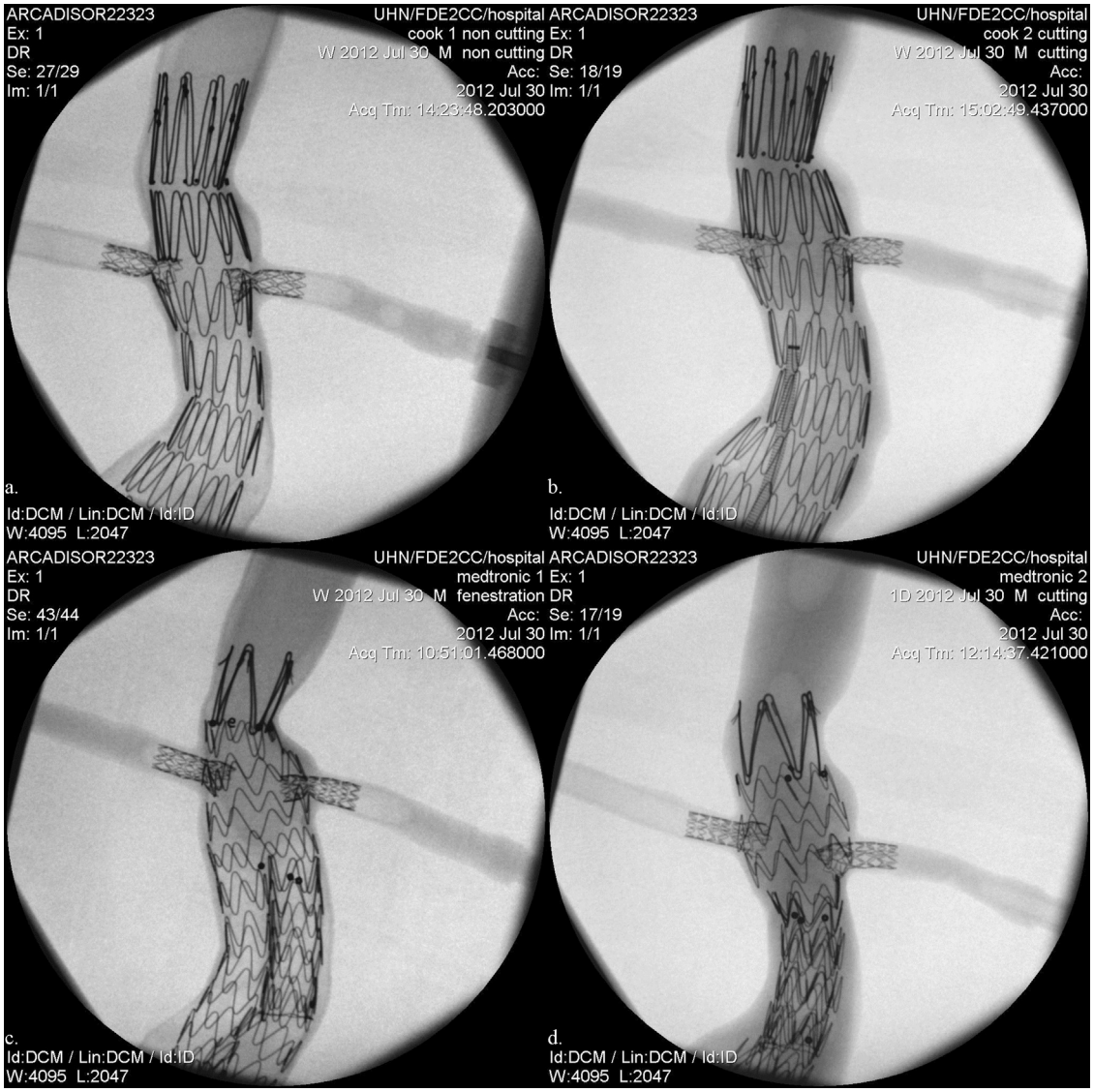

Figure 2. Fluoroscopic images after suprarenal deployment of fully assembled bifurcated aortic stent grafts and in situ fenestration of bilateral renal arteries with covered stents in **(a)** a Cook Zenith device with use of a 4-mm conventional angioplasty balloon, **(b)** a Cook Zenith device with use of a 4-mm cutting balloon, **(c)** a Medtronic Endurant device with use of a 4-mm conventional angioplasty balloon, and **(d)** a Medtronic Endurant device with use of a 4-mm cutting balloon.

(weft) directions. The warp counts in the Cook device were higher near the fenestration compared with the nonfenestrated areas, suggesting that the yarns are "bunched" together in this direction, whereas there was little difference in the weft direction (**Table**). This finding is consistent with the shape of the fenestration being elliptical with the long axis in the longitudinal direction. Although the Medtronic fabric counts showed a similar pattern, there was much less difference in fenestrated and unfenestrated fabric counts in the warp direction for the cutting-balloon specimen. This finding may suggest that the blades of the cutting balloon cut the yarns, rather than pushed them together. The implication is that there may be less reinforcement of the yarn strength around such a fenestration (cutting balloon on Medtronic fabric). The yarns in the Cook graft fabric were also larger than the yarns in the Medtronic graft fabric and as such were likely stronger. The larger yarns would also contribute to the smaller fenestration area in the Cook grafts compared with the Medtronic grafts because the yarns would show more resistance to the balloon.

DISCUSSION

Previous work with in situ antegrade fenestration of the perirenal abdominal aorta showed that it is technically feasible in an animal model (3,6,7), and the gross examination of the fabric material from the 1-month in vivo studies did not show fabric tears beyond the fenestration (5,7). Additionally, acute analysis and fatigue testing of large numbers of simple fabric specimens showed fabric stability after in situ fenestration (19). The present study extends this work further by using patient-specific

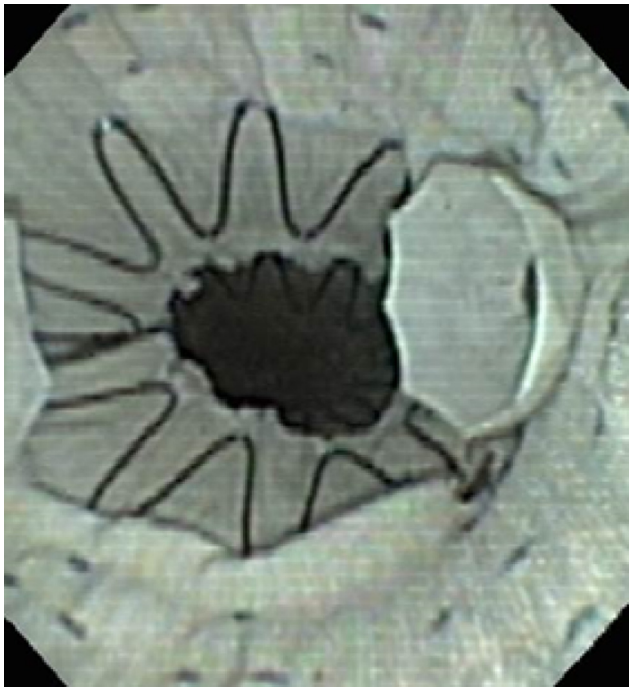

Figure 3. Representative video image from a medium-resolution endoscope of the renal covered stent from within the lumen of the aortic fenestrated stent.

phantoms and full stent graft constructs, cutting balloons, formal textile materials analysis, and pulsatile fatigue testing.

Our results suggest that the fabric material is not damaged beyond the fenestration at 40 million cycles (equivalent to 1 patient-year). Specifically, fraying and melting did not extend beyond the fenestration area of 6 mm. As expected, fraying was worse with the cutting balloon compared with the conventional balloon. It was worse with the Medtronic Endurant device compared with the Cook Zenith device. This is likely due to the weave structure of the Cook Zenith device that incorporates "floating yarns" that reinforce the fabric and prevent excessive fraying in the circumferential/weft direction. This study further showed that the cutting balloon helped increase the fenestration diameter, which would be needed with the Cook Zenith fabric, which was previously shown to be underdilated with conventional balloons (19). These experiments were performed on polyester-based aortic stent grafts only. Previous work reported significant difficulty puncturing polytetrafluoroethylene material with radiofrequency wires (19). A different puncture mechanism would be required for polytetrafluoroethylene-based devices, such as a mechanical needle (2).

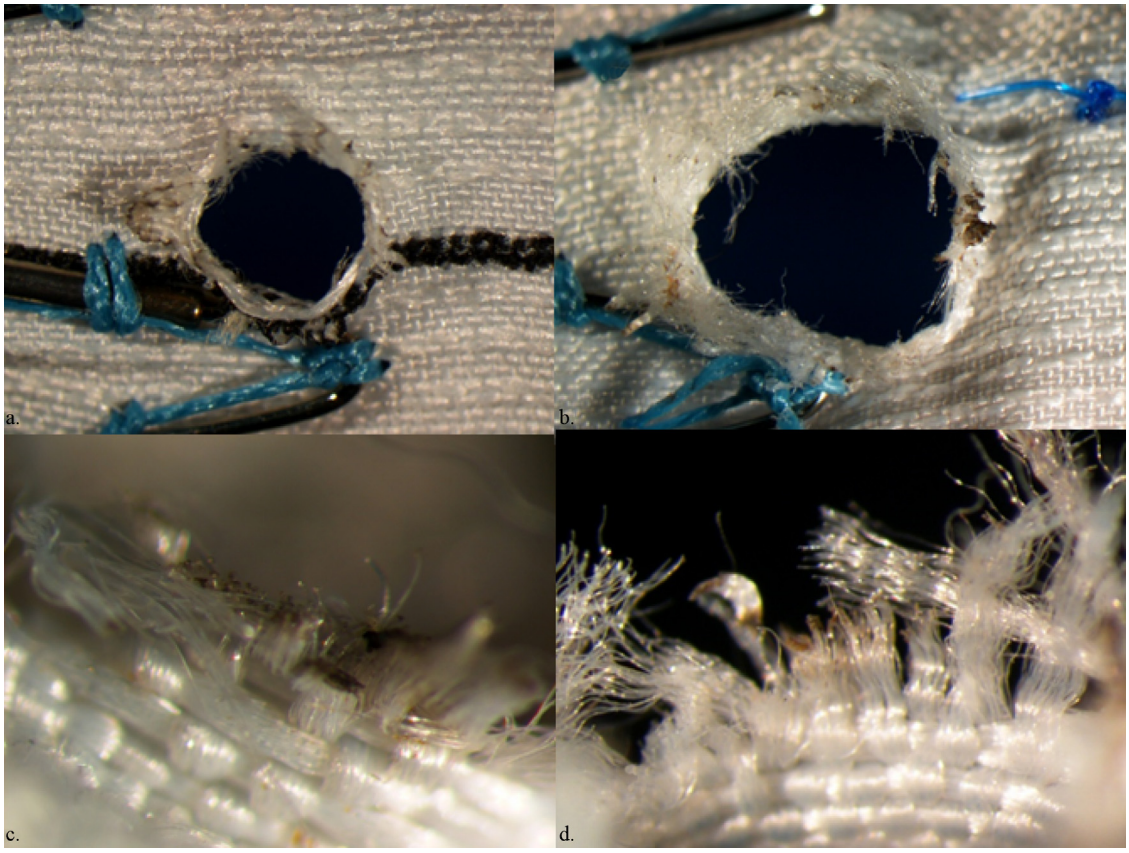

Figure 4. Images of fenestrations in the fabric of the Cook Zenith device with **(a)** a conventional angioplasty balloon, **(b)** a cutting balloon, **(c)** a conventional angioplasty balloon under 40 × zoom magnification, and **(d)** a cutting balloon under 40 × zoom magnification.

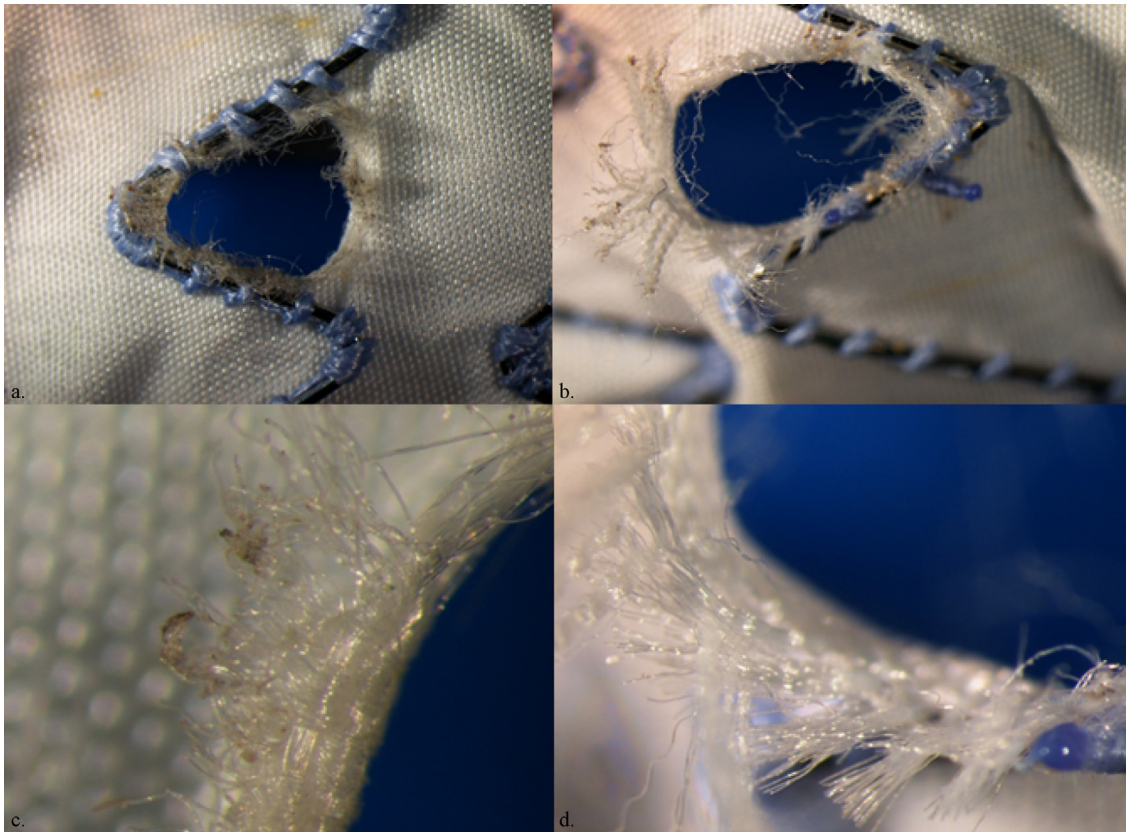

Figure 5. Images of fenestrations in the fabric of the Medtronic Endurant device with **(a)** a conventional angioplasty balloon, **(b)** a cutting balloon, **(c)** a conventional angioplasty balloon under 40 × zoom magnification, and **(d)** a cutting balloon under 40 × zoom magnification.

Table. Fabric Counts Around Fenestrated and Unfenestrated Areas

			Fabric Count (Average Picks/2.5 cm)	
Device	**Balloon**	**Location**	**Warp**	**Weft**
Cook Zenith	Noncutting	Right renal	256	294
		Left renal	269	288
		Unfenestrated area	200	288
Cook Zenith	Cutting	Right renal	288	288
		Left renal	281	256
		Unfenestrated area	225	263
Medtronic Endurant	Noncutting	Right renal	297	319
		Left renal	344	319
		Unfenestrated area	263	288
Medtronic Endurant	Cutting	Right renal	303	319
		Left renal	269	281
		Unfenestrated area	288	313

From a clinical point of view, our study suggests that if the Cook Zenith device is being used, a cutting balloon would be necessary for adequate fenestration size. If using the Medtronic Endurant device, cutting balloons would be unnecessary for adequate fenestration size and may cause an excessive amount of fraying. For both scenarios, in situ fenestration size did not exceed the planned 6-mm diameter of the Atrium covered stents. This finding implies that the fabric defect would not enlarge with multiple cycles of fatigue, and type 3 endoleaks from junctional gaps are unlikely to form because of fatigue. Additionally, the flaring of the covered renal stent may help reinforce this junction. Given that it is balloon expandable, the covered renal stent could mold and fill in any irregularities in the graft fabric fenestration.

This study has a few limitations. The experiments were conducted as a proof of concept study rather than an analytic study. One of the primary limitations is the limited number of specimens tested, which is in part due to the high cost of full aortic stent grafts and covered stents. Similarly, because of the length of time necessary to complete a single fatigue study, we performed fatigue testing only to an interim time point of a single patient-year. Future studies would ideally incorporate testing of 400 million cycles to simulate 10 patient-years. Our testing was with pulsatile pressure only and does not include other "in vivo" effects such as flow and shear. However, the validity of "accelerated" flow modeling to simulate long-term fatigue would be inappropriate in a bench model. This study does not include the impact of respiratory variation on the renal branches. The translational movement of the kidneys was well demonstrated in previous studies evaluating renal stents using the computational technique of finite element analysis (22). For experimental validation and testing, translational motion, in an accelerated manner, is significantly more difficult; however, this was not possible for this proof of concept study. Our next work on the thoracic aorta will include such motion. Our study used only two types of balloon catheters, and there are many different balloons available with differing properties and behaviors. Additionally, it is unknown whether a lack of contact with body-temperature blood has any effect on the ability to dilate the fenestrations. Finally, the anatomy of the particular patient on which the phantom was based presented very favorable renal artery configurations. It is anticipated that clinical cases would be more challenging and may require a brachial or axillary approach for more typical down-going renal arteries. Despite the favorable anatomy of our phantom, we could not precisely control the perforation angle, which has been shown to be important in the quality of fenestrations (18); the use of bendable directional or robotic sheaths and other creative techniques may be beneficial in future studies.

In conclusion, this proof of concept experimental work in a patient-specific phantom model suggests that the renal fenestrations created during in situ fenestration of juxtarenal endovascular aneurysm repair do not expand beyond the target diameter despite cyclic fatigue at 40 million cycles (1 patient-year). Although the small number of devices tested and selected aortorenal anatomy in this study may limit conclusions, textile analysis suggests that cutting balloons should be used for the Cook Zenith device, and conventional balloons should be used for the Medtronic Endurant device.

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