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## Research Letter

# Assessing Differences in Aortic Haemodynamics Between Two-Vessel Versus Four-Vessel Fenestrated Endovascular Aneurysm Repair using Patient-Specific Computational Flow Simulation

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Fenestrated endovascular aneurysm repair (FEVAR) techniques require the protrusion of target vessel stent grafts into the aortic flow lumen, which has been associated with turbulent flow patterns in the adjacent aorta and may adversely affect downstream haemodynamics.<sup>1,2</sup> Recent advances in computational flow simulation (CFS) have enabled quantification of physiological haemodynamics in cardiovascular pathologies, but have seldom been applied to study complex EVAR in a patient-specific manner.<sup>2,3</sup> We aimed to use patient-specific CFS to investigate haemodynamic differences between patients treated with two-vessel (2V) versus four-vessel (4V) FEVAR, with a focus on how additional graft fabric protrusion into the aortic lumen effects renovisceral perfusion and aortic laminar flow patterns.

This was a dual centre, retrospective study involving patients treated with FEVAR (Cook Zenith Fenestrated Platform; Cook Medical Inc., Bloomington, IN, USA) between January 2016 and May 2019 at Rennes University Hospital (Rennes, France) and Stanford University (Stanford, CA, USA). All available 4V FEVAR patients at Rennes University Hospital with juxtarenal aortic aneurysm (JRAA) and suprarenal aortic aneurysm (SRAA) pathology and without post-operative graft related complications (e.g. proximal endoleak, target vessel stenosis or occlusion) were selected. An endograft diameter-matched cohort of patients treated with 2V FEVAR at Stanford University with JRAAs and SRAAs was then identified. Patients in the 2V cohort received stented fenestrations in the bilateral renal arteries with an unstented large fenestration for the superior mesenteric artery (SMA), and patients in the 4V cohort received stented fenestrations in the coeliac, SMA, and bilateral renal arteries. Target vessel stenting

was performed in a similar fashion at each institution, with the use of balloon expandable covered stents flared with compliant angioplasty balloons sized 2 mm greater than the fenestration diameter.

Methods for patient-specific flow simulations using open source SimVascular software (Open Source Medical Software Corp., San Diego, CA, USA) have been previously described.<sup>1</sup> Briefly, pre-operative and the first post-operative (within 30 days of index procedure) computed tomography angiograms were used to extract patient flow geometry. Allometrically scaled inlet and outlet boundaries were then applied, and pulsatile rigid wall flow simulations were performed. Haemodynamic parameters in the aorta and branches were then compared between the 2V and 4V groups, with a focus on renovisceral perfusion metrics (pressure and flow rate), time averaged wall shear stress (TAWSS), and flow turbulence in the paravisceral aorta. The study protocol was approved by each institution's respective ethics committee.

Pre- and post-operative patient-specific flow simulations were performed on 10 patients undergoing 2V FEVAR and 10 patients undergoing 4V FEVAR. Overall device and anatomic characteristics between the groups were similar, with no significant differences in median (interquartile range) aneurysm diameter [2V vs. 4V, 59 (56, 60) mm vs. 56 (51, 65) mm;  $p = .42$ ], infra-SMA seal length [15 (8, 23) mm vs. 16 (8, 22) mm;  $p = .89$ ], or angulation [ $12^\circ$  (0, 30) vs.  $10^\circ$  (5, 25);  $p = .46$ ] between groups. Renal stent flare protrusion length [4 (4, 5) mm vs. 5 (4, 6) mm;  $p = .26$ ], stent diameter [7 (6, 7) mm vs. 6 (6, 7) mm;  $p = .11$ ], and overall stent length [29 (22, 29) mm vs. 26 (22, 27)

mm;  $p = .20$ ] were also similar. Main body device diameters were matched between cohorts and ranged between 28 mm and 36 mm.

When evaluating post-operative changes in renovisceral perfusion, we found that compared with 2V FEVAR, 4V FEVAR peak flow rate  $\Delta$  was significantly reduced in the SMA [ $+1.0$  ( $-1.2, 4.8$ ) mL/s vs.  $-3.6$  ( $-5.0, -1.6$ ) mL/s;  $p = .035$ ]. Moreover, 90% ( $n = 9$ ) of patients treated with 4V FEVAR had a reduction in SMA flow compared with 40% ( $n = 4$ ) of patients treated with 2V FEVAR. Overall, the magnitude of flow rate reduction was small, with most patients experiencing a  $< 15\%$  relative reduction in SMA peak flow. There were no significant differences in coeliac ( $p = .68 - .98$ ) or renal ( $p = .14 - .26$ ) perfusion metrics.

Stratified by cohort, 4V FEVAR resulted in a consistent reduction in paravisceral aortic TAWSS compared with patients treated with 2V FEVAR [ $+0.02$  ( $-0.13, 0.56$ ) dynes/cm<sup>2</sup> vs.  $-0.63$  ( $-1.85, -0.26$ ) dynes/cm<sup>2</sup>;  $p = .003$ ] (Fig. 1A). On three-dimensional velocity streamline analysis, irregular flow patterns with relatively lower particle velocity were observed in regions immediately inferior to flared branch grafts. These regions were frequently observed after 4V FEVAR owing to the presence of additional flared branch grafts in the coeliac artery and SMA. In all patients treated with 2V FEVAR, regions of flow disturbance were limited to the infrarenal aorta. A representative TAWSS contour and velocity streamline map in a 4V FEVAR patient is illustrated in Figure 1B.

In summary, we have found that patient-specific CFS reveals subtle changes in SMA perfusion, and potential adverse effects on aortic TAWSS and flow pattern disruption after 4V FEVAR of pararenal aortic aneurysms compared with 2V repair. Identifying potential haemodynamic differences between graft geometries may have important implications regarding risk of branch thrombosis and intraluminal thrombus formation, particularly as lower TAWSS is a known risk factor for intraluminal thrombus deposition in the aorta and aortic endografts.<sup>4,5</sup> Significant limitations exist with our findings, including possible selection bias given the retrospective nature of the study. Differences in aortic morphology proximal to the repair, boundary conditions, and total treated aortic length between cohorts were also not adjusted for. Future prospective, larger cohort studies are required to clinically validate these findings and to correlate changes in simulated haemodynamics with adverse clinical events.

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## **<H1>ETHICAL APPROVAL<H1>**

The study protocol was approved by each institution's respective ethics committee (University of Rennes #16.38; Stanford University #58565).

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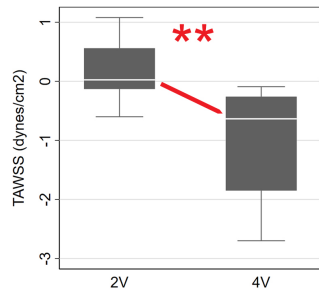
**Figure 1.** (A) Relative changes in paravisceral aortic TAWSS stratified by 2V and 4V fenestrated endovascular aneurysm repair groups. \*\*  $p < .010$ . (B) Three-dimensional contour plots demonstrating decreased paravisceral aortic TAWSS post-operatively after 4V repair. Regions of subphysiological TAWSS (black arrowheads) predominate in regions adjacent to flared branch graft ostia. These areas correspond to areas of non-laminar low velocity flow patterns (magenta arrowheads) in the aortic flow lumen. TAWSS = time averaged wall shear stress; 2V = two vessel; 4V = four vessel.



**Figure 1 – (A)** Relative changes in paravisceral aortic time-averaged wall shear stress [TAWSS] stratified by 2-vessel [2V] and 4-vessel [4V] fenestrated EVAR groups. \*\* =  $p < .01$  **(B)** Three-dimensional contour plots demonstrating decreased paravisceral aortic TAWSS post-operatively after 4V repair. Regions of sub-physiologic TAWSS (black arrows) predominate in regions adjacent to flared branch graft ostia. These areas correspond to areas of non-laminar low velocity flow patterns (magenta arrows) in the aortic flow lumen.

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