Flow and wall shear stress characterization after endovascular aneurysm repair and endovascular aneurysm sealing in an infrarenal aneurysm model

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ABSTRACT

Background: Endovascular aneurysm repair (EVAR) with a modular endograft has become the preferred treatment for abdominal aortic aneurysms. A novel concept is endovascular aneurysm sealing (EVAS), consisting of dual endoframes surrounded by polymer-filled endobags. This dual-lumen configuration is different from a bifurcation with a tapered trajectory of the flow lumen into the two limbs and may induce unfavorable flow conditions. These include low and oscillatory wall shear stress (WSS), linked to atherosclerosis, and high shear rates that may result in thrombosis. An in vitro study was performed to assess the impact of EVAR and EVAS on flow patterns and WSS.

Methods: Four abdominal aortic aneurysm phantoms were constructed, including three stented models, to study the influence of the flow divider on flow (Endurant [Medtronic, Minneapolis, Minn], AFX [Endologix, Irvine, Calif], and Nellix [Endologix]). Experimental models were tested under physiologic resting conditions, and flow was visualized with laser particle imaging velocimetry, quantified by shear rate, WSS, and oscillatory shear index (OSI) in the suprarenal aorta, renal artery (RA), and common iliac artery.

Results: WSS and OSI were comparable for all models in the suprarenal aorta. The RA flow profile in the EVAR models was comparable to the control, but a region of lower WSS was observed on the caudal wall compared with the control. The EVAS model showed a stronger jet flow with a higher shear rate in some regions compared with the other models. Small regions of low WSS and high OSI were found near the distal end of all stents in the common iliac artery compared with the control. Maximum shear rates in each region of interest were well below the pathologic threshold for acute thrombosis.

Conclusions: The different stent designs do not influence suprarenal flow. Lower WSS is observed in the caudal wall of the RA after EVAR and a higher shear rate after EVAS. All stented models have a small region of low WSS and high OSI near the distal outflow of the stents. (J Vasc Surg 2016;■:1-10.)

Clinical Relevance: Most endografts for endovascular aortic aneurysm repair involve a modular stent design, and the design could vary in the location of the flow divider. Endovascular aneurysm sealing based on polymer filling of endobags surrounding dual stent frames was recently introduced. This study focuses on effects of a dual-lumen configuration in the abdominal aorta after endovascular aneurysm sealing on flow and wall shear stress proximal and distal to the stents in comparison with two endovascular aneurysm repair endografts and an aneurysm control by in vitro flow visualization.

Endovascular aneurysm repair (EVAR) has become the standard treatment for infrarenal abdominal aortic aneurysms (AAAs). The procedure is related to a lower 30-day mortality rate[1] and shorter rehabilitation period in comparison to open surgical repair. Most endografts involve a modular bifurcated design in which fixation and seal are provided by radial force in the landing zones or proximal fixation with hooks. Stent design varies in the position of the flow divider, the presence of suprarenal fixation, and the attachment of the fabric to the stent frame (exoskeleton or endoskeleton). Endovascular aneurysm sealing (EVAS), whereby the AAA is sealed by polymer-filled endobags surrounding dual 10-mm cobalt-chromium balloon-expandable endoframes, was recently introduced.

The dual-lumen configuration after EVAS is different from an anatomic or EVAR stent bifurcation with a tapered trajectory of the flow lumen into the two limbs.

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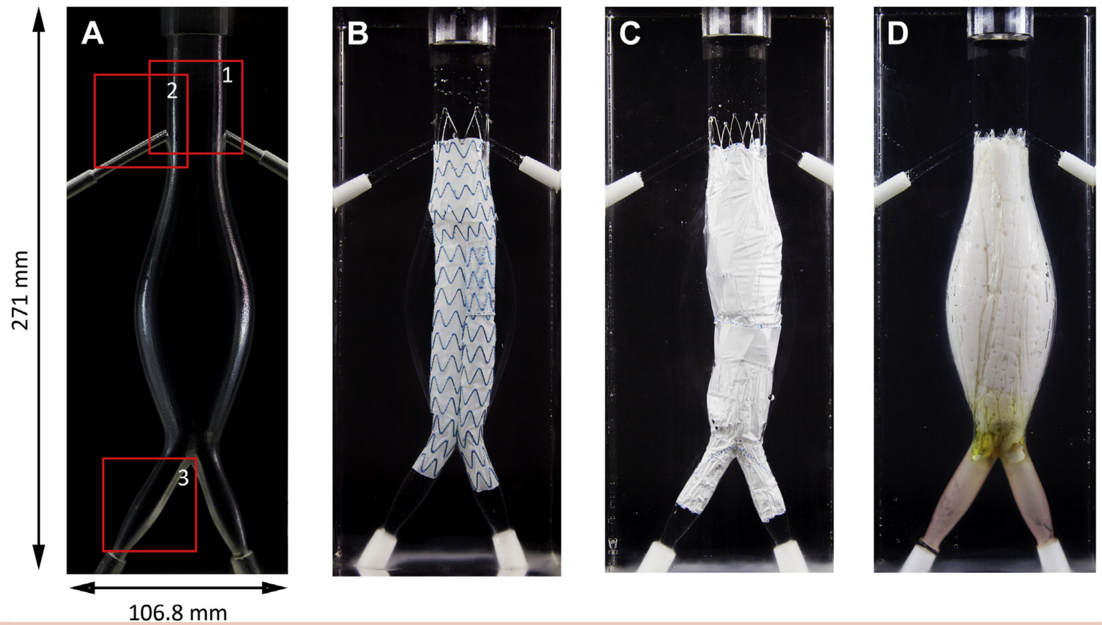

Fig 1. Flow models. **A,** Nonstented, control; indicated are the two-dimensional measurement planes where the flow was captured in the center of the flow lumen. The numbers refer to the three regions of interest: *1,* suprarenal aorta; *2,* right renal artery (RA); and *3,* right common iliac artery (CIA). **B,** Endurant endovascular aneurysm repair (EVAR). **C,** AFX EVAR. **D,** Nellix endovascular aneurysm sealing (EVAS).

This difference in stent design may have different implications regarding flow patterns in the aorta and branch arteries proximal and distal to the stents in comparison with standard modular grafts. A potential mismatch area between the native vessel lumen and the EVAS stents may result in flow recirculation at the transition between the stents and the vessel lumen in the aorta and common iliac arteries (CIAs). Moreover, the transition of the aorta into two 10-mm stents after EVAS may increase vascular resistance, wall shear stress (WSS), and velocity into renal branches.

WSS is defined as the force per unit area acting parallel to the vessel wall due to the local velocity gradient. Low WSS is associated with atherosclerosis[2,3] and subsequent atherothrombotic events,[4,5] and it may occur in regions that present flow recirculation. A low WSS has been defined as <1 Pa for arteries in vivo,[6,7] whereas only extremely low magnitudes (ie, 10^{-2} Pa) have been associated with development of atherosclerosis and blood coagulation.[2,8] Moreover, directional changes in WSS throughout a cardiac cycle (ie, periodic oscillations in WSS) may be found in areas of flow recirculation and have also been associated with development of atherosclerosis.[2,9] A high shear rate (>5000 s^{-1}), referring to the gradient of the local flow velocity near the vessel wall, is associated with acute thrombosis.[10]

The study focuses on effects of a dual-lumen configuration in the abdominal aorta after EVAS on flow and WSS proximal and distal to the stents in comparison with two EVAR endografts and an aneurysm control by in vitro flow visualization.

METHODS

Flow models. Flow phantoms based on an inverse negative mold of a three-dimensional printed AAA model were fabricated (Fig 1, *A*).[11,12] Model geometry was based on a straightforward AAA anatomy with an infrarenal neck diameter of 28 mm, infrarenal neck length of 15 mm, and maximum AAA diameter of 55 mm. A summary of the aortoiliac anatomy of the flow model is provided in Table I. The final design was molded in transparent silicone (Sylgard 184; Dow Corning, Midland, Mich) for optical transparency required for flow visualization. Three different endosystems were implanted: the Endurant II (Medtronic, Minneapolis, Minn), the AFX (Endologix, Irvine, Calif), and the Nellix (Endologix). The flow dividers of the Endurant and AFX are situated 5 cm distal to the most caudal renal artery (RA) and at the native bifurcation, respectively. These models were compared with a control (Fig 1). Stent planning, sizing, and deployment in the models were performed following the standard instructions for use by experienced vascular surgeons (M.M.P.J.R. and J.-P.P.M.V.).

Flow setup. Flow tests were performed under physiologic resting conditions. The setup was based on a two-parameter Windkessel model, including a compliance chamber downstream of the phantom to simulate peripheral vessel impedance.[13] In brief, a pulsatile flow at a rate of 60 beats/min was generated with a physiologic flow rate in a range of 1.6 L/min (peak flow, 3.6 L/min). The inlet section consisted of a 1.2-m tube to ensure a fully developed laminar flow entering the model. At the start