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Impact of alterations in target vessel curvature on branch durability after endovascular repair of thoracoabdominal aortic aneurysms

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Objective: **The aim of this study was to evaluate curvature and its effect on the durability of visceral and renal branches in patients undergoing endovascular repair of thoracoabdominal aortic aneurysms (TAAAs) with fenestrated/branched endovascular aneurysm repair (F/B-EVAR).**

Methods: **Quantitative branch vessel curvature assessment on branches arising from reinforced fenestrations was performed for 168 patients undergoing F/B-EVAR for type II and type III TAAAs. Preoperative and postoperative centerline coordinates were obtained using iNtuition (TeraRecon, Foster City, Calif) and exported into MATLAB (The MathWorks, Inc, Natick, Mass) based on thin-slice computed tomography imaging. Spline interpolation was applied to the centerline coordinates and resampled at 100 equally spaced points, and curvature calculations (κ, mm^{-1}) were applied. Global and maximal curvatures for each of the target vessels were measured and categorized by severity. Categories for curvature were 0 to 0.05 mm^{-1} (low), 0.05 to 0.1 mm^{-1} (medium), 0.1 to 0.15 mm^{-1} (high), and >0.15 mm^{-1} (extreme) for global curvature and 0 to 0.2 mm^{-1}, 0.2 to 0.4 mm^{-1}, 0.4 to 0.6 mm^{-1}, and >0.6 mm^{-1}, respectively, for maximum curvature. Curvature variances were assessed for an association with vessel patency and need for reintervention.**

Results: **There were 558 vessels that underwent analysis based on repairs involving 650 vessels, whereby 92 vessels were excluded as they were treated with an external helical branch (58 celiac arteries and 34 superior mesenteric arteries). There was a significant difference found before and after F/B-EVAR for the global celiac artery curvature (median difference, −0.01; $P < .001$), global left renal artery curvature (median, −0.01; $P = .014$), maximum left renal artery curvature (median, 0.05; $P < .001$), and maximum right renal artery curvature (median, 0.03; $P = .009$). Maximum artery curvature was found to have shifted distally in all vessels postoperatively; 37 adverse events (AEs) were observed in 30 patients (6 branched occlusions and 31 reinterventions [24 type III endoleaks, 5 vessel stenoses, and 2 vessel occlusions]). The majority of AEs (>70%) occurred within the range of low to medium curvature. Univariate analysis found gender to be a dependent variable associated with high (maximum) preoperative curvature (odds ratio, 0.395; $P = .02$). The use of self-expanding stents (vs balloon-expandable stents alone) in vessels with high preoperative curvature (>0.6 mm^{-1}) was significant in the right renal artery ($P = .044$).**

Conclusions: **This study did not show a significant relationship between the severity of artery curvature or changes in curvature and AEs found for visceral or renal branches after F/B-EVAR for extensive TAAA. Surprisingly, the majority of AEs occurred in low- and medium-curved vessels. This study is limited in that it does not take into account other factors that may affect AEs, like motion, which would be valuable in future studies. (J Vasc Surg 2016;63:634-41.)**

Endovascular therapy for the treatment of aortic disease has evolved significantly during the past two decades. Current technologies allow the treatment of increasingly complex aortic disease, including thoracoabdominal aortic aneurysms (TAAAs). These systems rely on the durable connection between the main aortic body and the distal target vessels, including the celiac artery (CA), superior mesenteric artery (SMA), and renal arteries. To bridge the aortic stent graft main body to the target vessel, two main branching systems have been employed that involve a bridging stent mating with either a directional branch (straight or helical) or a reinforced fenestration.[1,2] The directional branches are typically mated with the target vessel using a self-expanding stent (SES) graft, whereas reconstructions based off of a reinforced fenestration use a balloon-expandable stent (BES) graft. The use of covered BES grafts not only allows treatment of more extensive aneurysmal disease in which the origin of the target vessel does not need to lie within the seal zone, but it may be associated with improved patency rates.[3]

Initial patency and long-term durability appear to be excellent with fenestrated/branched endovascular aneurysm

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repair (F/B-EVAR).[2,4,5] Relatively low rates of reintervention are required to treat endoleak development, occlusions, or stenosis. The results, however, appear to be more favorable for visceral target vessels (CA and SMA) compared with the renal arteries.[4,6] There are a number of factors that may contribute to loss of patency or the need for reintervention in these complex endograft systems. Some of these are in the mechanical properties of the components of the stent graft systems themselves.[6] Others are the result of the endograft systems altering the physiology and anatomic morphology of the aorta and its branches.[3] In fact, the presence and extent of the TAAA can alter the anatomy of the visceral vessels, in particular the renal arteries, changing the directional nature of the vessel as well as adding angulation and curvature along its trajectory.[7] Addressing highly curved visceral and renal vessels during F/B-EVAR can be challenging. Adjunctive procedures and devices are frequently employed by physicians treating distal target vessels that have significant curvature or are tortuous, specifically the additional use of SESs.[8] These configurations use a BES mating with a reinforced fenestration proximally and the subsequent placement of an SES distally to ease the transition from the stiff BES to the tortuous, more compliant target vessel. It is not known whether the presence of these challenging tortuous target vessels, the alterations in their morphology with the introduction of stiff stent graft systems, or the need for an additional SES plays a role in determining their long-term patency or need for reintervention.

The aim of the study was to evaluate the effect of vessel curvature on the durability of visceral and renal branches arising from reinforced fenestrations in patients undergoing repair of TAAA with F/B-EVAR. We hypothesized that higher preoperative target vessel curvature would be associated with higher rates of target vessel adverse events (AEs). In addition, the presence of higher preoperative target vessel curvature would be associated with an increased adjunctive use of SESs.

METHODS

Study cohort. This retrospective analysis was conducted on 168 patients who underwent F/B-EVAR for Crawford type II and type III TAAAs between June 2010 and December 2013. Given the different angulations at which renal arteries arise between Crawford type IV TAAAs and more extensive TAAAs,[7] initial analysis was limited to the more extensive aneurysms. Endografts were placed under a physician-sponsored investigational device exemption protocol, and informed consent was obtained from patients for their participation; this analysis was approved by the Cleveland Clinic Institutional Review Board (No. 4281). Details of the patient population and methods of device implantation have been described previously.[1] Thin-slice computed tomography (CT) imaging was completed preoperatively and postoperatively, and routine follow-up visits were performed with repeated duplex ultrasound and thin-slice CT cross-sectional imaging within 30 days of the index procedure and then on an annual basis. The CA, SMA, left renal artery (LRA), and right renal artery (RRA) were the focus of branch vessel curvature assessment. Vessels included for analysis were those that were stented with a reinforced fenestration and a BES; those treated with a helical directional branch and bridged with an SES (usually the CA, SMA, or both) were excluded.

Image acquisition. Contrast-enhanced CT scans were acquired using non-electrocardiographically synchronized, spiral acquisition of the chest, abdomen, and pelvis. A noncontrast-enhanced phase was obtained when the stent was in place, and arterial and delayed venous phases were obtained for all patients. The scanners used during the study period were Siemens Definition Flash (Siemens Healthcare, Erlangen, Germany) and Philips iCT (Philips Healthcare, Cleveland, Ohio) with at least 65 detectors. Preoperative and postoperative CT images were analyzed and centerline coordinates for each vessel were constructed using Aquarius iNtuition (TeraRecon, Foster City, Calif). Once the centerline constructs were obtained and visually verified to be correct, they were exported to MATLAB (The MathWorks, Inc, Natick, Mass). Along with the centerline coordinates, image resolution, field of view (FOV), image slice spacing, and number of images per scan were recorded for the conversion of the centerline units. The mean number of images per scan was 798.6 ± 20.5 lines (range, 514-1014).

Centerline coordinates. The centerline was first obtained in postoperative imaging. The centerline started at the ostium of the visceral or renal vessel and ended at the first bifurcation point (Fig 1). This length was recorded as a reference in obtaining the coordinates from the preoperative imaging. The coordinates that were already mapped were then subtracted back from the first bifurcation point to the distal end of the branching device to reveal a set of centerline coordinates that would cover only the region of stent graft coverage. This region was used as a reference to ensure that overlapping preoperative and postoperative centerlines were obtained in the stented region. Curvature analysis was not limited to the stented region but extended into the native vessel beyond the stent. After the target vessels were completed, the preoperative centerlines were obtained in a similar fashion. The coordinates were then exported to MATLAB along with resolution, FOV, spacing, and number of images per scan.

A conversion factor was needed to convert the centerline from units of pixels to units of millimeters. This was done as follows:

$$(x, y)pixels \times \frac{FOV\ (mm)}{Resolution\ (pixels)} = (x, y)mm$$

$$(z)pixels \times \frac{spacing(mm)}{slice(pixels)} = (z)mm$$

The cumulative sum of the centerline was then calculated to verify that the conversion was correct by comparing the calculated length with the length provided by iNtuition. To smooth the centerline curve and to eliminate some abnormalities, a spline was applied and the centerline was