The Hemodynamic Impact of Misalignment of Fenestrated Endografts: A Computational Study

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WHAT THIS PAPER ADDS
This paper investigates the influence of variable stent-graft orientation on the displacement forces and stresses acting on different parts of fenestrated endografts. The variability in take-off angulation of stent-grafts affects the stresses acting on the mated target vessels. The conclusion of our computational study provides valuable information for delineating the hemodynamic performance of branched endografts.

Objective: The hemodynamic consequences of misaligned stent-grafts (SG) in fenestrated endografts (EG) have not been adequately studied. Our aim was to study the hemodynamic effects of positional variations of SG, investigating the potential influence on the total displacement forces acting on the EG and the shear stress values at the stented segments.

Methods: This was a computational study. An idealized EG model with two renal fenestrations was computationally reconstructed and centrally extended up to the suprarenal level to treat a suprarenal aneurysm. The misalignment of SG was represented by a variable take-off angle between the SG and the EG centerline axis, corresponding to angles of 90°, 176°, 142°, 38°, and 4°, respectively. Accordingly, the maximum EG displacement forces and the shear stress within the stented segments were calculated, using commercially available software.

Results: The variable positions of the SG caused no effect on the maximum displacement force acting on the EG, being quite steady and equal to 5.55 N. On the contrary, the values of maximum shear stress acting on the stented segments were influenced by their orientation. The narrow transition zone between the distal end of the mating stent and the target artery showed higher stresses than any other segment. The right-angle take off SG position (90°) was associated with the lowest stresses (12.5 Pa), whereas the highest values were detected at 38° and 142° (16.5 and 16.1 Pa, respectively). The vessel segments distal to the SG exhibited constantly lower stress values (1.9–2.2 Pa) than any other segment.

Conclusion: We detected differences in the values of shear stress exerted on the stented arteries, depending on different positions that SG can adapt after the deployment of fenestrated EG. The pathophysiologic implication of our findings and their potential association with clinical events deserve further investigation and clinical validation.

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INTRODUCTION
Endovascular devices used to treat suprarenal (SAAA) and juxtarenal (JAAA) abdominal aortic aneurysms incorporate fenestrations through which directional stent-grafts (SG) protrude into the involved aortic target vessels, most commonly the renal arteries, to maintain perfusion. The success of endovascular repair depends heavily on the proper preoperative planning, comprising a precise and detailed measurement of the centerline from the top of the endograft’s (EG) cranial landing zone to the center of each target vessel ostium. The assessment of the orientation, clock position, angle of incidence and diameter of the ostia are also of paramount importance.

Ideally, the orientation and route of mating SG should match the corresponding patient’s vessel distribution as closely as possible, avoiding any misalignment, angulation, or inadequate protrusion into the target vessel. However,
in practice, multiple variations from the ideal plan may be encountered, as a result of errors in main EG deployment associated with long endograft main body, narrow, calcified, or tortuous iliac arteries, which can lead to a considerable degree of mismatch between visceral vessel and EG fenestration orientation with consequent misalignment. These factors can compromise the optimal positioning and, hence, influence the hemodynamic performance of stent grafts. The planned SG orientation does not always lie on the centerline of the aorta, nor is the axial orientation of the fenestrations easy to control or predict intraoperatively, as the exact position is documented adequately by the radio-opaque markers only after the EG deployment, rendering any repositioning attempts afterwards either difficult or risky. Moreover, geometrical alterations occurring postoperatively during the aneurysm’s sac shrinkage process can lead to migration and dislocation of either the EG main body or the SG, with resultant Type I or III endoleaks, kinking, and angulation of these segments.

The variable geometrical configurations adapted by the endograft SG as a result of misalignment can influence the shear stress magnitude and distribution on the endograft’s SG, as well as on the junction between the SG and the target visceral vessel, predisposing to subsequent myointimal hyperlasia, stenosis, and occlusion. Therefore, we sought to investigate the influence of misalignment of SG on the hemodynamic performance of the entire EG and the stented segments (i.e. mated vessels), as expressed by the EG displacement forces and the shear stresses on the SG and target vessels. Our estimations were based on computational AAA models and fluid dynamics simulations, which have been described and used extensively in the past for assessment of the factors determining the hemodynamic behavior of endovascularly treated AAA.

**MATERIALS AND METHODS**

Initially, a 3D model of an AAA was reconstructed, based on typical values of an AAA (Table 1). Using these values, cross-section profiles were constructed and interpolated to form the geometric body of the AAA. Accordingly, a customary

<table>
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<tr>
<th>Table 1. Geometric characteristics of the abdominal aortic aneurysm (AAA) reconstructed 3D model.</th>
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<tr>
<td><strong>Aneurysm model</strong></td>
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<tr>
<td>Inlet diameter (R1)</td>
</tr>
<tr>
<td>Iliac outlet diameter (R2)</td>
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<tr>
<td>Renal outlet diameter (R3)</td>
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<tr>
<td>Aneurysm diameter (R4)</td>
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<td>Aneurysm length (L1)</td>
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<td>The dimensions above are depicted in Fig. 1B.</td>
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<table>
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<th>Table 2. Geometric characteristics of the endograft (EG) reconstructed 3D model.</th>
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<tr>
<td>Inlet diameter (R1)</td>
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<tr>
<td>Iliac outlet diameter (R2)</td>
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<tr>
<td>Renal outlet diameter (R3)</td>
</tr>
<tr>
<td>Inlet segment length (L2)</td>
</tr>
<tr>
<td>Iliac segment length (L3)</td>
</tr>
<tr>
<td>Renal segment length (L4)</td>
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<tr>
<td>Curvature radius</td>
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<td>The dimensions above are depicted in Fig. 1B.</td>
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bifurcated 3D EG model with two renal SG was computationally created using the parameters shown in Table 2, corresponding to typical EG dimensions found in the literature. Cross-section geometry profiles were introduced (Fig. 1A) and interpolated (Fig. 1B) to form the model of an EG treating a SAAA, where both renal arteries would be mated to SG (Fig. 1C). The construction of the EG model was completed by adding cylindrical segments of length 6-fold inlet diameter \( L_5 = 144 \text{ mm} \) and 5-fold the renal outlet diameter \( L_4 = 30 \text{ mm} \) above the inlet of the EG and after the insertion of SG into the renal ostia, respectively, resembling normal segments where flow velocity profiles could be fully developed before entering the EG’s main body and shear stress values computed at segments corresponding to both renal arteries after the mating site (Fig. 1B).

The take-off angle between the renal SG and EG centerline axis was set as an input parameter in order to study the effect of misaligned SG. Ideally, the renal SG of the EG should radiate towards the renal ostia transaxially, at a right angle with respect to the EG main body, preserving optimal flow. However, studies on the anatomy of juxtarenal and thoracoabdominal aneurysms have shown that renal arteries tend to adopt most often a downward

**Figure 2.** Orientation of the endograft’s stent-grafts ranging from the most caudal to the most cephalad position (A–E), multiple values of take-off angles between the renal SB and the EG centerline axis being 4°, 38°, 90°, 142°, and 176°.
(caudal) direction in type IV thoracoabdominal aneurysms, whereas an upward (cranial) direction is met more frequently in more centrally located aneurysms.\textsuperscript{3,15–17} Therefore, in order to represent the misalignment of renal SG, our reconstructed models included multiple values of take-off angles between the renal SG and the EG centerline axis, being 4°, 38°, 90°, 142°, and 176°, moving from caudally to cephalad (Fig. 2A–E).

Computational fluid dynamics (CFD) analysis was performed to simulate blood flow and blood pressure. The commercially available software ANSYS (Ansys Inc., Canonsburg, PA, USA) was used for the mesh construction of the geometric models (Fig. 3) and for solving the equations for conservation of momentum and mass for incompressible fluid in order to describe the flow fields. For purposes of model-geometry discretization, a computational mesh was constructed with 20,262 nodes and 93,463 elements.

No-slip boundary conditions were chosen for the EG wall, and the velocity and pressure waveforms during a period of 1 second, as previously reported by Figuroa et al.,\textsuperscript{18} were used as velocity inlet and pressure outlet boundary conditions at iliac and renal sites (Fig. 4A–C, respectively). The resultant waveforms were discretized in time with 50 equal time-steps. For the computational analysis a transient convergence criterion was used so that pressure and velocity had a deviation of less than 0.01%. Four cycles were required for most of the cases to achieve transient convergence. Blood was assigned as non-Newtonian fluid, according to the Carreau-Yasuda model, 

\[
\mu = \mu_\infty + \left( \mu_0 - \mu_\infty \right) \left( 1 + \frac{\lambda \gamma}{\alpha} \right)^{\frac{1}{\alpha}}
\]

with a density of 1050 kg/m\textsuperscript{3}, where: \( \mu_0 = 0.022 \) Pa s, \( \mu_\infty = 0.0022 \) Pa s, \( \lambda = 0.11 \) s, \( n = 0.392 \) and \( \alpha = 0.644 \).

Using these techniques, the maximum total displacement force acting over the entire EG during the cardiac cycle was calculated for all reconstructed models. The maximum shear stress values were calculated in three distinct segments of the SG—renal artery (Fig. 5): the SG segment originating from the EG main body and mating the renal vessel (zone 1); the narrow transition zone between the distal end of the SG and the renal artery (zone 2); and the post-mating vessel segment (zone 3).

RESULTS

The variable angulations of the SG caused no effect on the maximum displacement force acting on the EG (Fig. 6A), being quite steady and equal to 5.55 N. On the contrary, the values of maximum shear stress acting on the SG and

![Figure 3. Mesh creation of the reconstructed model.](image-url)

![Figure 4. The velocity and pressure waveforms used in our reconstructed model as inlet and outlet boundary conditions at the supraceliac level (A), the iliac (B), and renal sites (C) for a period of 1 second.](image-url)
mating segments were influenced by the direction of the SG branches (Table 3). The narrow transition zone (Zone 2) between the distal end of the mating stent and the target vessel (Fig. 7A) showed higher stress values than the proximal SG (Zone 1) or the peripheral arterial segment (Zone 3) (Fig. 7B).

**DISCUSSION**

In order to treat complex and challenging aortic aneurysms extending to or above the renal level, recent technical developments have enabled the use of fenestrated EG. Fabric holes of fenestrated EG are positioned adjacent to the aortic branch artery orifices and secured by deploying smaller, covered or uncovered stents through the fenestrations and into the arterial branches.1,2 It has been shown that fenestrated EG offer better fixation compared with infrarenal EG with suprarenal bare stents because of additional SG support.19,20 Interestingly, measurements for planning fenestrated endovascular repair of thoracoabdominal aneurysms are prone to significant intra- and interobserver discrepancies.21 The misaligned side-branches after EG deployment caused by inappropriate or insufficient preoperative measuring could theoretically lead to stenosis or occlusion of the stented vessels. Furthermore, conformational changes such as EG migration, longitudinal movement, or rotational torque, buckling or kinking have been reported to occur during the post-implantation aneurysm shrinkage process,22 affecting the alignment and initial position of side branches. Therefore, our aim was to study the hemodynamic effects of a misalignment in orientation of endograft’s SG by investigating the potential influence on the proximal displacement forces acting on these EG and the shear stress values within the SG and stented vessels.

Our EG model corresponds to an endograft of two renal fenestrations, whereas the perfusion of a more cephalad vessel (e.g. superior mesenteric artery) could be practically served by a simple scallop. This configuration is met quite often according to a recent review reporting the number of}

Table 3. Maximum shear stress values (Pa) at different sites of the stent-graft—target vessel.

<table>
<thead>
<tr>
<th>Take-off angle</th>
<th>Zone 1</th>
<th>Zone 2</th>
<th>Zone 3</th>
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<tbody>
<tr>
<td>4°</td>
<td>10.986</td>
<td>14.09a</td>
<td>1.938b</td>
</tr>
<tr>
<td>38°</td>
<td>11.4</td>
<td>16.467a</td>
<td>1.975b</td>
</tr>
<tr>
<td>90°</td>
<td>8.291</td>
<td>12.447a</td>
<td>2.297b</td>
</tr>
<tr>
<td>142°</td>
<td>10.76</td>
<td>16.083a</td>
<td>1.955b</td>
</tr>
<tr>
<td>176°</td>
<td>10.258</td>
<td>15.336a</td>
<td>2.238b</td>
</tr>
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Zone 1: stent extending from the endograft to the target vessel; Zone 2: transition zone at the distal end of the mating stent; Zone 3: post-mating target vessel segment.

a The highest values at Zone 2 are approximately 50% higher than the mating stent segment (Zone 1).

b The lowest stress values induced in the post-stenting segment and predisposing to intimal hyperplasia. These values are equivalent, with very narrow range.
renal, celiac, and superior mesenteric fenestrations in eight studies with fenestrated EG for treatment of PAAA/JAAA. It was shown that the majority of patients (i.e. 68–75%) required only two renal fenestrations, thus rendering our model quite applicable to clinical reality.\(^2\) Additionally, this pattern (i.e. renal fenestrations and one scallop) is also shared by newer EG for endovascular repair of JAAA, such as the Ventana fenestrated system, let alone that a greater number of fenestrations is associated with increased technical difficulties and preoperative morbidity.\(^2\)\(^4\),\(^2\)\(^5\) As confirmed by our results, the magnitude of the forces leading to migration of the EG is not influenced by the orientation of the SG; rather, their mating into the renal arteries provides sufficient anchoring compared with standard aortic EG, irrespective of their take-off angles.

Although misalignment between native aortic anatomy and fenestrations has been shown to generate compressive forces acting on the SG used to secure these fenestrations, some SGs can remarkably withstand the stenosis or deformation caused by these “crushing” forces.\(^2\)\(^6\),\(^2\)\(^7\) On the other hand, discrepancies in side-arm SG might lead to undesired stress and strain on the bridging stent mating the target vessels (as for the renal arteries in our case), predisposing to poor patency of the SG and the target vessels.\(^1\)\(^6\)

Stent implantation generates endothelial flow disturbances, altered blood flow patterns and intramural stress concentrations in the vessel wall, which are influenced by the stent design and spacing, the conformational change in size and geometry of the stented vessel as well as the compliance mismatch between stent and artery.\(^8\),\(^9\),\(^2\)\(^8\)–\(^3\)\(^0\)

Generally, low shear stress patterns are associated with induction of intimal hyperplasia and in-stent stenosis, whereas high stress values correlate with endothelial damage and stent material fatigue, predisposing to local thrombogenic activity and subsequent compromise of the lumen patency.\(^3\)\(^1\) The regional geometry encountered

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**Figure 7.** Shear stress estimation at the stent-graft and the related arterial segment. The transitional zone at the distal mating end (A) presents higher values than the central stent or the peripheral arterial segment (B).
immediately after stent implantation may predispose segments of the stented vessel to a higher risk of neointimal hyperplasia and subsequent stenosis.\textsuperscript{3,7,8,28,29,31}

The difference in the etiologic factors implicated in the development of stenosis in patients treated with uncovered or covered stents has been reported by Mohhabat et al.,\textsuperscript{32} who reported that covered stent stenosis occurs only at the distal stent edge (i.e., the “transitional” zone between mating-stent and renal artery of our models), whereas uncovered stent stenosis occurs at both the proximal and distal segments of the stent. The distal stenosis of the covered stent seems to be associated with geometric changes of the particular segment (such as those induced either during the respiratory movements) or with the additional arterial tortuosity shifted distally after the placement of the mating stents.\textsuperscript{32} Investigating the hemodynamic influence of fenestrated stent insertion on the renal arteries, Sun and Chaichana observed a slight post-insertion reduction in wall shear stress of the renal arteries, whereas uncovered stent stenosis occurs at both the proximal and distal segments of the stent. The distal stenosis of the covered stent seems to be associated with geometric changes of the particular segment (such as those induced either during the respiratory movements) or with the additional arterial tortuosity shifted distally after the placement of the mating stents.\textsuperscript{32} The discrepancies of the stress values in our study could be attributed to the variable orientations of the SG. The highest values adjacent to the distal end of the stent were approximately 50% higher than the mating stent segment (Zone 1) and, more interestingly, almost one order of magnitude higher than the stresses in the peripheral post-stenting vessel wall (Zone 3, Table 3), which was subjected to much lower stresses with very narrow range of values (1.9–2.2 Pa). Spatial differentiations in shear stresses (between Zones 2 and 3 in our example) have been postulated by many studies to induce and enhance myointimal hyperplasia.\textsuperscript{34–37}

The 90° SG was associated with the lowest stress in Zones 1 and 2 (i.e., stent-graft and transitional zone), but the stress values were comparable between the different geometries. On the other hand, the most interesting finding - constant for all geometries - was the abrupt decrease of stresses across the distal end of the stent. The hemodynamic environment described above could predispose to comparable risk of intimal hyperplasia. Accordingly, we believe that these factors justify and favor long-term antiplatelet therapy and/or statins, which might down-regulate these processes. The improvement of stent-graft mechanics and profile (flexibility, compliance mismatch between stents and arterial wall, degree of stent oversizing, crush resistance, efficacy to withstand kinking) may further attenuate intimal hyperplasia.\textsuperscript{30}

Sobocinski et al.\textsuperscript{38} recently reported on successful management of 70% of patients with JAAA with two different types of such endografts, which differed in the lengths of the superior mesenteric artery to renal fenestration and renal-to-renal fenestration. As the 6-mm renal fenestrations had to align to variable positions of renal ostia, this must have led to different orientations of the stents. Therefore, the comparable stress patterns and values between the different SG geometries of our study may encourage the practice of standardized, “off-the-shelf” fenestrated EG for a significant percentage of PAAA or JAAA,\textsuperscript{39} or even justify the authors’ impression that their EG could accommodate for an even greater proportion of aneurysms, resulting even in a “chimney effect”, with bridging stents traversing a gap between the EG and the aortic wall.\textsuperscript{38}

The chimney technique is based on the deployment of a covered or bare metal stent parallel to outside of the aortic endograft, entering the target vessel ostia in 90°.\textsuperscript{40} As large evidence is lacking to compare for mid- or long-term results on clinical and hemodynamic performance between chimney and fenestrated EG,\textsuperscript{41} computational simulation studies may provide useful information examining for differences in the flow pattern and stress values in the SG between the two accommodations under similar boundary conditions (pressure, flow velocity, etc.). Apart from fenestrated EG, side-branched EG with branches that can spiral around the EG body offer an alternative solution towards an off-the-shelf EG approach for complex AAA (pararenal, juxtarenal, or thoracoabdominal).\textsuperscript{1–3} The clinical and hemodynamic comparison between these accommodations remains an issue for future research.

**LIMITATIONS**

A number of assumptions were made for our calculations. The creation of EG models was based rather on idealized geometries than patient-specific reconstructions. The EG walls were assumed to be undeformable, rigid rather than elastic. The blood was assigned to be non-Newtonian according to the Carreau-Yasuda model and the pressure at the exit of both limbs was assumed to have the same waveform. Our computational model did not take into account the visceral branches but was constrained in the simplest form, that is two side-branches, corresponding to renal arteries. Further studies with more complex computational models (i.e., patient-specific geometries with more than two fenestrations and SG) will add more to the understanding of complex EG performance. The extraction and comparison of our results was focused on different geometries of the SG and did not take into account the modeling of renal-protruding-stents, the thickness and length of which could affect the hemodynamic outcomes of our study;\textsuperscript{33} nevertheless, as our aim was the comparative study of stresses depending solely on geometrical differences, we believe that the lack of specific stenting-material modeling does not obscure the comparison of our results.

The SG-protruding segment into the EG lumen was not simulated. A recent computational study considering this effect, showed no significant alterations in flow patterns or wall shear stress post-fenestration.\textsuperscript{33} Our study did not also take into account the relative movements of the EG parts and the renal arteries during the cardiac cycle (and respiration), although these are limited after the stenting of

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fenestrations, compared with standard EG. Future studies should involve these parameters to determine their specific effect on shear stress distribution.

In conclusion, different positions of SG after the deployment of fenestrated EG for the treatment of PAAA and JAAA do not affect the total displacement forces acting on the entire EG while influencing the distribution and affecting moderately the values of shear stresses acting on different segments of the mating SG. The clinical implication of these findings and their potential association with adverse effects, such as stenosis, thrombosis, endoleaks, component separation, and stent fracture, deserve further investigation and clinical validation.

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CONFLICT OF INTEREST
None.

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