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Blood Flow in a Healthy Abdominal Aorta Versus Configurations of Aneurysmatic Abdominal Aortas Post 'Chimney' Endovascular Repair

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1. Abstract

In recent years, more aortic aneurysm repairs are performed endovascularly using stent grafts (SGs). In this study, we analyze the hemodynamics in an aneurysmatic abdominal aorta (AAA) endovascularly repaired by a stent graft (SG) system using the chimney technique. Computational fluid dynamics (CFD) is employed to study models of a healthy aorta versus an aorta post 'chimney' endovascular aneurysm repair (ChEVAR) using chimney stent grafts (CSG). Results demonstrate that the presence of the CSGs results in stagnation regions and wall shear stress (WSS) modifications, yet the flow regime remains laminar.

Keywords: chimney endovascular aneurysm repair (ChEVAR), Abdominal Aortic Aneurysm (AAA), Chimney Stent Grafts (CSG), Hemodynamics, Wall Shear Stresses (WSS)

2. Introduction

In recent years, more aneurysm repairs are performed endovascularly, excluding the aneurysm sac using stent grafts (SGs) inserted into the aneurysm site through the arterial system (minimally invasive). Following SG implantation, the aneurysm sac is sealed and blood subsequently flows through the newly created artificial conduit replacing the bulging part of the aorta.

In urgent cases, where the patient cannot wait several months for a custom SG system to be fabricated, an innovative solution is recently being employed using off-the-shelf SGs. This solution involves an endovascular surgical procedure called the 'chimney' technique whereby parallel to the main aortic SG that excludes the aneurysm sac, one or more tubular covered stents ('chimneys') are inserted into the visceral arteries. These covered stents facilitate proper blood flow to arteries that would otherwise be blocked by the main aortic SG due to their proximity to the aneurysm sac. A common case of aneurysm repair using the 'chimney' technique is the two renal arteries being highly adjacent to the aneurysm. Thus, requiring a chimney stent graft (CSG) in each renal artery to preserve blood flow to the kidneys.

In this study, a healthy abdominal aorta was evaluated in comparison with several configurations of post ChEVAR aorta having CSG inserted into each renal artery (Figure 1). Computational fluid dynamics (CFD, ANSYS Fluent package) simulations of pulsatile blood flow during the cardiac cycle were employed. An idealized anatomy of the abdominal aorta was modeled based on averages of measurements taken from cadaver specimens and patient angiograms (Moore *et al*, 1992). The effect of CSGs on abdominal aortic blood flow and wall shear stresses (WSS) was analyzed by examining blood flow patterns and regimes.

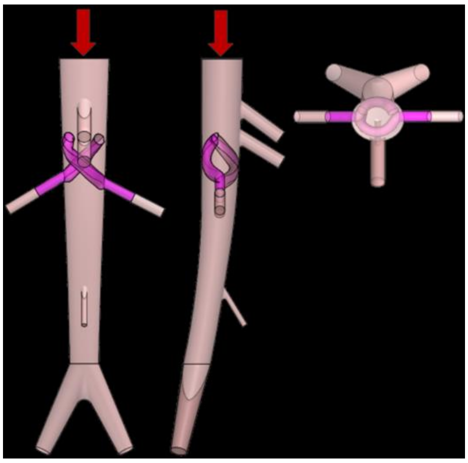

Figure 1: 3D model of the post ChEVAR abdominal aorta for analysis (aneurysm replaced by SG). Left to right: Front, side and top views, respectively. Red arrows: direction of blood flow.

3. Methodology

Anatomical Model

The model incorporates the elliptical cross section, the tapering nature of the abdominal aorta, the arterial branches and the slight curvature towards the posterior wall. The model of the abdominal aorta post ChEVAR is based on the healthy model. Modifications were made in the model in order to account for the CSGs. The bulging part of the abdominal aorta is assumed completely replaced by the aortic SG, and thus is not a part of the numerical domain. The CSGs protrude upstream into the aorta 10 mm above the main SG to avoid blockage of blood flow into the renal arteries.

Numerical Model

Blood flow behavior in the abdominal aorta during the cardiac cycle is considered to be predominantly laminar (Morris et al, 2004). Thus, a laminar CFD solver is employed. Literature demonstrates flow parameters e.g. WSS differ by as much as 30% between distensible and rigid blood vessel models (Shipkowitz et al, 1998). However, overall flow dynamics remain similar (Friedman et al, 1992). Thus, rigid wall approximation is sufficient for a comparative study. No slip/penetration boundary conditions are applied at the walls. The inlet boundary condition employed is a pulsatile velocity function adapted from the literature (Taylor *et al*, 1998).

Numerical Discretization

The model of the post ChEVAR abdominal aorta was meshed using 1.1 million polyhedral cells with 4 million nodes. The cycle time was discretized into 800 time steps. The scaled residuals value used was 5·10-6. The numerical parameters used for the healthy aorta model were similar.

4. Results

Flow Patterns

Stagnant regions are formed in the post ChEVAR aorta downstream near the CSGs. These regions persist throughout the cardiac cycle (Figure 2). There are no stagnant regions in the healthy model (Figure 3).

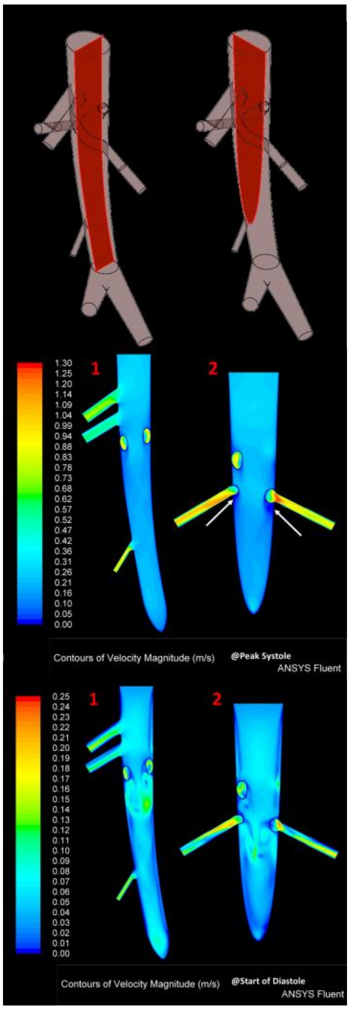

Figure 2: Post ChEVAR abdominal aorta. Top: planes of velocity contours are marked in red. Middle: Velocity contours at peak systole. Bottom: Velocity contours at diastole beginning.

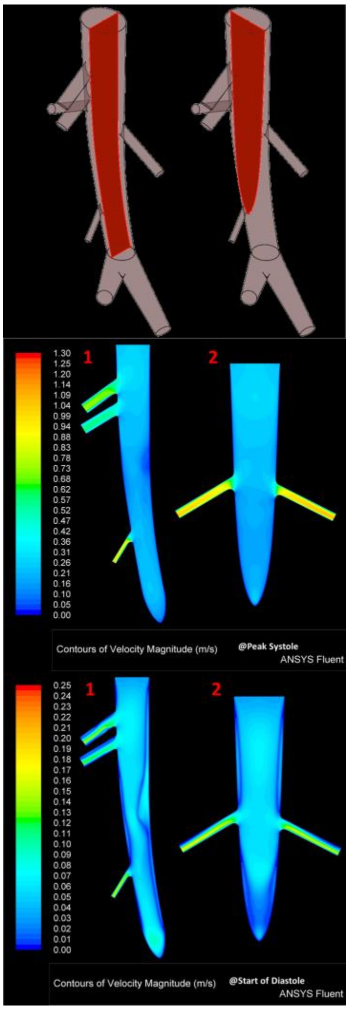

Figure 3: Healthy aorta. Top: planes of velocity contours are marked in red. Middle: Velocity contours at peak systole. Bottom: Velocity contours at diastole beginning.

Flow Regime

Y (axial) component of the WSSs for the aorta post ChEVAR at various positions and distances from the inlet (according to Figures 4 and 5) are plotted in Figure 6 through Figure 8. Y component of the velocity along the centerline is plotted in Figure 9. The WSSs and the velocity follow the inlet velocity waveform. There are no high frequency components present. If the inlet blood flow waveform is free of high frequency components yet points inside the control volume present velocity/WSS waveforms with high frequency noise then the flow exhibits transitional regime behavior. If the waveforms are free of high frequency components/noise, it indicates a laminar flow regime (Bozzetto *et al*, 2015). This implies that the flow in the post ChEVAR abdominal aorta is free of transitional behavior and is indeed laminar.

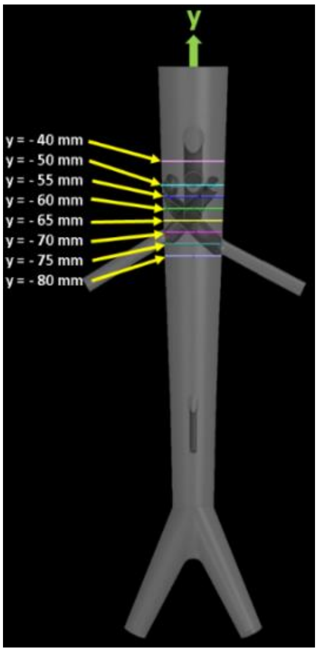

Figure 4: Section planes and their distances from the inlet.

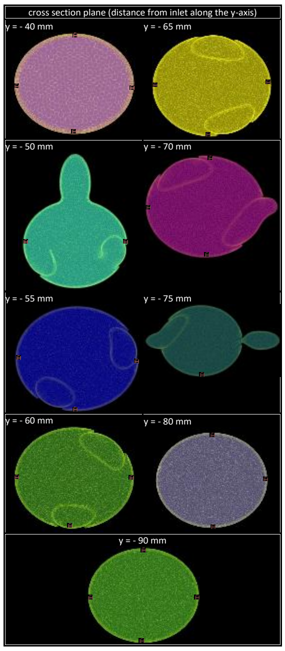

Figure 5: ⊕ Points evaluated for WSSs at different horizontal planes.

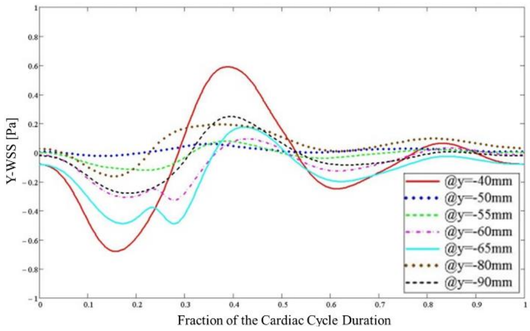

Figure 6: Y/axial component of WSS along the right side of the post ChEVAR aorta during the cardiac cycle.

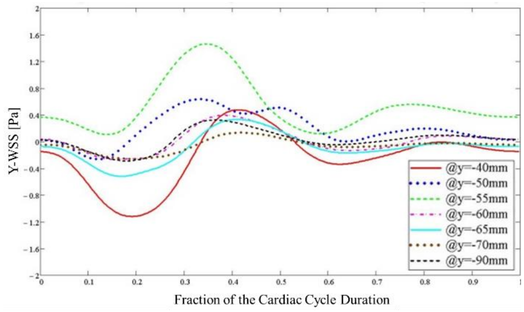

Figure 7: Y/axial component of WSS along the left side of the post ChEVAR aorta during the cardiac cycle.

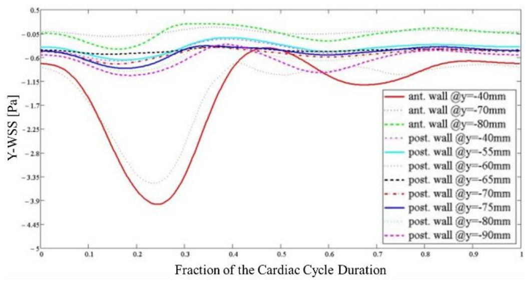

Figure 8: Y/axial component of WSS along the anterior and posterior of the post ChEVAR aorta during the cardiac cycle.

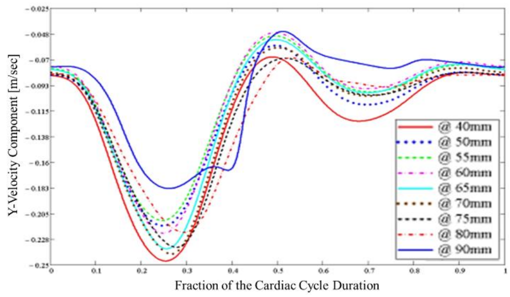

Figure 9: Y/axial component of velocity along the centerline of the post ChEVAR aorta.

5. Discussion and Conclusions

Our results suggest that CSGs presence in the abdominal aorta introduces variations in blood flow patterns and the formation of stagnant regions downstream from the CSGs throughout the cardiac cycle, potentially contributing to thrombosis (Ku *et al*, 1997). However, as can be deduced from the smooth and non-disturbed nature of the curves portrayed in Figure 6 through Figure 9 and in accordance with a previous study, the CSGs do not cause the flow regime to become turbulent or transitional (Bozzetto *et al*, 2015). This indicates limited flow field changes due to CSGs, thus further supporting the predictability of the flow in the abdominal aorta following an implantation of two renal stent grafts. These findings reconcile with data indicating a relatively high success rate in ChEVAR procedures performed in recent years, evident both in short and long-term patient follow ups (Zhang *et al*, 2015).

6. References

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