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Fluid-structure interaction (FSI) analysis of 3D printing personalized stent-graft for aortic endovascular aneurysm repair (EVAR)

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Abstract. Abdominal aortic aneurysm (AAA) is an irreversible dilation of abdominal aorta, which may rupture if not surgically treated. To date, most aorta stent-graft used in clinical practice are batch manufactured devices with a uniform diameter. Custom abdominal aortic stent-grafts are able to overcome standard stents limitations. In this study, a customized aortic stent-graft (NiTi - Dacron) for the treatment of AAA has been proposed. Fluid dynamics analyses were performed to deepen the hemodynamic of aneurysm vessel and the proposed patient-specific graft. By means this study, the authors have shown the real benefits of the device for the patient and the possibility to apply this new stent-graft in the near future.

Introduction

Abdominal aortic aneurysms (AAAs) are irreversible dilations of the abdominal aortic wall due to gradual weakening and remodeling, which alter physiologic blood flow patterns. AAA is defined as a permanent localized dilation of an artery with a 50% increase in diameter compared with expected normal diameter [1, 2]. The risk of AAAs increases of above 60 years population with a major incidence in men (four to six times more common in men than in women [3]), and in patients who present cardiovascular diseases, history of smoking or family history of aneurysmal disease. Progression of the disease can ultimately result in rupture of the abdominal aorta, which has mortality rates of 50-75% [4]. The surgical options for the aneurysm treatment include the conventional Open Surgical Repair (OSR) and the Endovascular Aneurysm Repair (EVAR). OSR is an invasive procedure consisting of a large incision on the site of aneurysm in order to remove and replace it by a synthetic graft. Treatments vary depending on the patient's condition and on a case-to-case basis. Choices include open-surgery procedures which are largely invasive or endovascular aneurysm repair (EVAR). Size and structure mismatch between standardized stent and aorta may cause internal leakage or rupture of blood vessels. With the development of precision medicine, personalized vascular stents that conform to the patient's true vascular structure have become the purpose of the next generation stents. EVAR has clear benefits in terms of less trauma, reduced mortality and lower morbidity.

Nevertheless, it has also limitations related to the anatomy and the morphology of the patient vessel and major post-operative complications may still occur due to stent graft migration and endoleaks. The conventional geometry are, in some cases, not compliant with the patient's blood vessels and the mismatch may cause internal leakage, rupture and the failure of EVAR treatment. For these reasons, the patient-specific stent grafts are considered the next generation of device, able to accommodate the patient's anatomical vascular structure. Hemodynamics is believed to play a key role in the formation and the progression of the dissecting aneurysm [7]. These numerical methods can provide detailed information about wall stresses and fluid flow. Several

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study of AAA by means of computational models have been reported in literature [8–11]. Over the years, Computational Fluid Dynamics (CFD) analysis and, in the last decade, Fluid-Structure Interaction (FSI) are used to simulate the complex cardiovascular system.
The aim of the work is to evaluate the advantages of using a patient-specific stent graft for EVAR treatment by means FSI analysis. In this preliminary study, a case of abdominal aortic aneurysm was examined by means of CFD in order to compare hemodynamics in the proposed patient-specific graft with respect to fluid dynamics in abdominal aortic aneurismatic vessel and in a conventional graft, ideally implanted after aneurysm resection by means OSR.

Materials and Methods

Image Segmentation and Model Construction.

The three-dimensional model of the patient's aneurismatic aorta was reconstructed from the patient's CT images using the software Mimics 21.0 (Materialise). The first step in the reconstruction process is the image segmentation to highlight the region of interest, the aorta in this specific case. Based on this, to perform the CFD analyses, the AAA model was obtained and conventional and the patient-specific grafts models were reconstructed in Solidworks®.

Geometry Discretization.

In the CFD approach, the continuous domain volume was discretized in approximate discrete domain. The three fluid models (i.e. aneurysmatic aorta, conventional and patient-specific grafts) were imported in .STL format in ICEM CFD 19.2 (Ansys Inc.) to discretize the volume in small elements and realize the mesh. For each model, *tetrahedral* elements in the core region and *prismatic* elements in the boundary layer (3 layers) were used. The mesh created consist of about 1 million elements with a mesh quality above 0.3, ratio between the volume of the element and the cube of the radius of the sphere that circumscribes it. In addition, meshes were verified in order to eliminate the unconnected vertices.

Computational Fluid Dynamics Analysis.

Fluid dynamics was evaluated by a transient CFD simulation performed using FLUENT v19.2 (Ansys Inc.). CFD solver is used to obtain an approximate solution of the Navier-Stokes differential equations.

$$\frac{D\rho}{Dt} + \rho\nabla \cdot \boldsymbol{u} = 0 \tag{1}$$

$$\rho\left[\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u}(\nabla \cdot \boldsymbol{u})\right] = -\nabla p + \mu\nabla^2\boldsymbol{u} + \rho g \tag{2}$$

where ρ is the density, ∇ is defined as $\nabla = \mathbf{i}\,\frac{\partial}{\partial x} + \mathbf{j}\,\frac{\partial}{\partial y} + \mathbf{k}\,\frac{\partial}{\partial z}$, u is the velocity, p is the pressure, μ is the viscosity, g the gravitational acceleration.

The analyses set-up are the same for all three fluid models.

The blood was assumed to be an incompressible and Newtonian fluid with a density ρ of 1060 kg/m^3 and viscosity μ of 0.003 Pa*s. Assuming a diameter of 0.5mm it is correct to assume a Newtonian flow through the aorta, in fact the blood viscosity is relatively constant at the high rates of shear (100 s^{-1}) typically found in the aorta [12]. The boundary conditions were imposed on inlet, outlets (abdominal, renal - branch1 and branch2 - and mesenteric) and the wall surfaces (Fig. 1). Mixed-type boundary condition represents physiological conditions more accurately because when the heart ventricles contract, it induces a change in volume that causes a pressure gradient and forces the blood out [13]. In addition, rigid and no slip conditions were assumed at wall. Two

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cardiac cycles have been simulated in order to achieve a solution independent from the initial conditions.

The investigated hemodynamic variables are Wall Shear Stress (WSS) and velocity. WSS in a blood vessel is the force per unit area created when tangential force (blood flow) acts on a surface (endothelium). The magnitude of WSS is proportional to the velocity gradient near the wall of the vessel, that is called wall shear rate:

$$\tau_w = \mu \left(\frac{\partial \gamma}{\partial t}\right)_{y=0} \tag{3}$$

Where μ is the dynamic viscosity, $\dot{\gamma}$ is shear rate and y the distance from the wall.

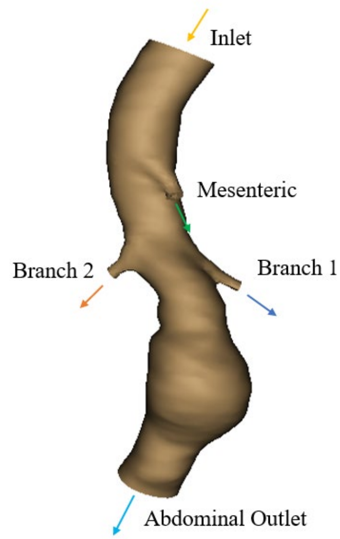

Figure 1 *CFD analysis set-up. The same surfaces are defined for both conventional graft fluid model and patient-specific graft fluid model*

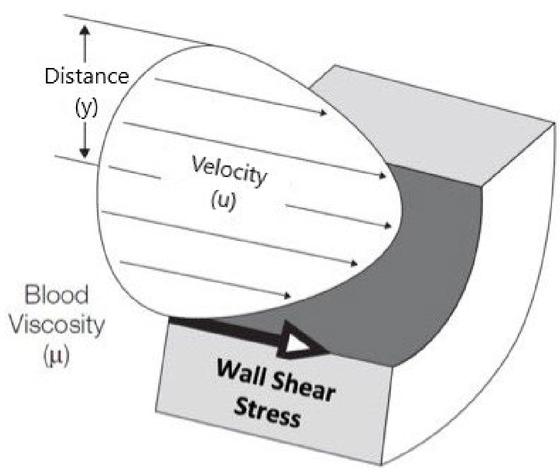

Figure 2 *Wall shear stress. The figure shows schematic illustration of the velocity profile experienced by inner surfaces of a vessel because of flowing blood*

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Results and Discussion

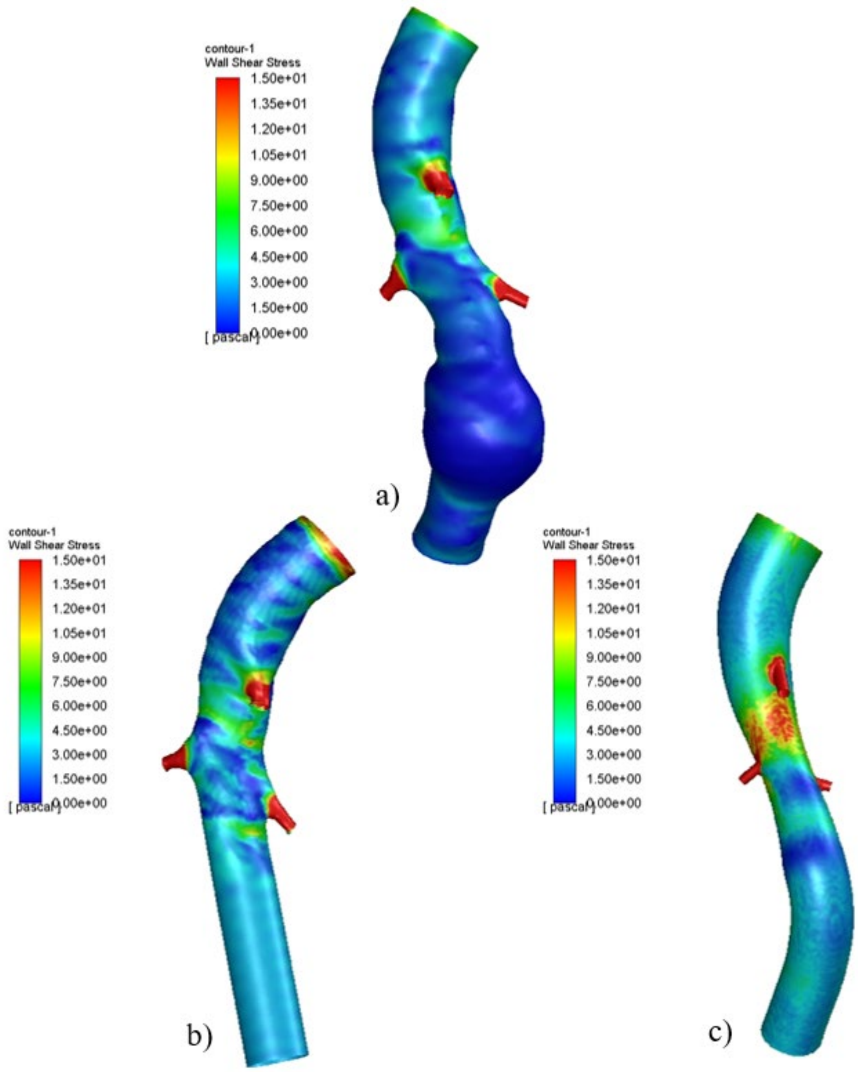

Figure 6 Wall Shear Stress at systole peak in a) aneurismatic aorta, b) conventional graft, c) patient-specific graft.

Wall shear stress (WSS) and velocity at peak systole are the hemodynamic in-depth variables in all three fluid models by CFD analyses. Fig. 6 shows the WSS in three fluid models. At the site of aneurysm, the WSS is zero (Fig. 6a). This indicates that blood flow does not exert tangential stresses on the wall due to the presence of low-velocity areas in the site as shown in Fig. 6a. The maximum WSS is located in branches: its value is of 184.6 Pa in aneurismatic vessel and the conventional graft (Fig. 6 a-b) compared to 142 Pa in patient-specific graft (Fig. 6c). The use of patient-specific graft reduces the maximum WSS of about 23% to the vessel and exhibits a distribution of wall shear stress more uniform than other models.

In Figure 7, the velocity magnitude of selected cross-sections is visualized at peak systole (0.313 s). Cross-section A is at aneurysm site, while cross-sections B and C are located in graft models at the same place of cross-section A. The use of both conventional and patient-specific graft removes the low-velocity area present in the aneurismatic vessel (Fig. 7a). The flow pattern in conventional graft (Fig. 7b) shows that the blood flow is not full developed and it is very different to the flow pattern of patient-specific graft (Fig. 7c). This aspect is associated to the conventional graft morphology and alters the vascular physiology. On the other hand, the flow pattern of patient-specific graft (Fig. 7c) is consistent and accommodates the vessel curvatures. The maximum of velocity is located in the branches in all three models.

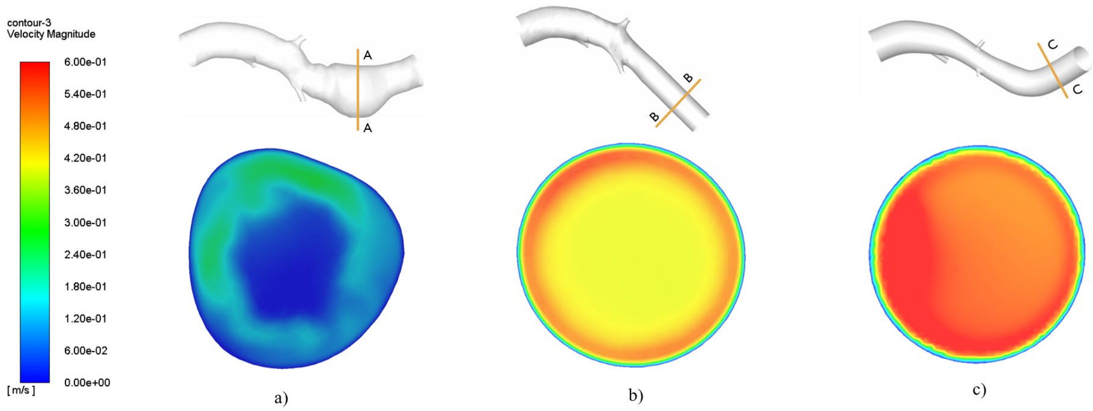

Figure 7 Velocity at systole peak in a) aneurismatic aorta, b) conventional graft, c) patient-specific graft.

Summary

In this work, we introduce a patient specific case study of the aortic aneurysm with the consequent design of a stent graft that can accommodate the complex anatomical structure of the patient. The device was modeled from abdominal aorta segmentation derived by CT scan images of abdomen. CFD, structural analysis and, more recently, the FSI are the numerical methods used for the study of cardiovascular disorders such as aneurysm even in patient specific cases. Computational methods were used in order to evaluate its hemodynamic advantages with respect to conventional graft. The fluid dynamics analysis carried out on the aneurysm vessel allowed to highlight salient aspects such as, first of all, the presence of flow recirculation and a high pressure profile. At the same time, it’s worth to note how the insertion of a patient specific graft is beneficial.

The blood flow inside does not present the zones at low speed, not altering the physiology and fluid-dynamic of the vessel (unlike conventional graft) with a consistent fluid pattern. In addition, patient-specific graft reduces the maximum WSS of about 23% to the vessel and conventional graft and exhibits a distribution of Wall Shear Stress more uniform than aneurismatic vessel. The future goal is to implement the fluid structure interaction of the patient specific stent graft in order to evaluate the behavior of the two materials and their interactions when subjected to the fluid forces and, consequently, of the device itself.

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