COMPUTER SIMULATION AND ANALYSIS OF HEMODYNAMIC CHANGES IN ABDOMINAL AORTIC ANEURYSMS TREATED WITH FENESTRATED ENDOVASCULAR GRAFTS

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ABSTRACT

The purpose of this study was to perform a simulation of blood flow and analyze the hemodynamic changes in patients with abdominal aortic aneurysms (AAA) treated with fenestrated stent grafts. Four patients with AAA undergoing multislice CT angiography pre-and post-fenestrated stent graft implantation were selected for inclusion in the study. Geometric models and hexahedral volume meshes were successfully generated for pre- and post-stent fenestrated implantation. The blood flow pattern was simulated inside the abdominal aortic aneurysm and arterial branches, as well as with a stent-graft in situ. Flow visualization showed that flow disturbances inside the aneurysm were apparently decreased and flow rate was significantly increased at the renal arteries after deployment of the fenestrated stents into these branches. The wall pressure was found to reduce inside the aneurysm sac following implantation of stent grafts. In this preliminary study, we successfully simulated the flow characteristics in abdominal aortic aneurysm before and after fenestrated endovascular repair.

1. INTRODUCTION

Endovascular insertion of stent grafts to repair the abdominal aortic aneurysm (AAA) has been confirmed to be an effective alternative to open surgery, especially in patients with co-morbid medical conditions [1, 2]. Since it was first introduced into clinical practice in 1991 by Parodi et al, endovascular stent graft repair of AAA has undergone a series of technical modifications, which range from conventional infrarenal fixation to suprarenal fixation of stent grafts [3-5]. The key criterion to determine the type of stent graft implantation is the anatomy of aneurysm neck, which is also the main limitation to successful endovascular repair of AAA. Presence of suboptimal aneurysm neck, which mainly includes a short (<10 mm) or angulated proximal neck (>60◦), presence of thrombus/atheroma or severe calcification in the neck excludes 30-40% of patients from the endovascular repair.

Fenestration stent-grafts have been developed to deal with the above problems [6, 7]. It was initially reported in 1999, which led to successful implantation in human subjects [6-8]. Fenestrated stent grafting enables the first sealing portion of the stent graft to be positioned in a more stable part of the aorta with the customized fenestrations at the exact origin of the targeted vessels. Fixation of the fenestration to the renal and other visceral arteries can be provided by implantation of bare or covered stents across the fenestrations so that a portion of the stents protrudes into the aortic lumen. Therefore, there are concerns about the loss of the target vessel resulting from the fenestrated technique. In addition, in most of the situations, there are about one-third of the fenestrated vessel stents protruding into the aortic lumen, which could lead to interference with hemodynamics following implantation of stent grafts [9].

Hemodynamics and biomechanics of an AAA following endovascular stent graft repair has been studied by researchers based on experimental or computational modeling studies [10-12]. Researchers investigated the dynamics of AAAs and stent grafts separately. However, all of these studies dealt with infrarenal or suprarenal fixation of stent grafts, and to the best of our knowledge, there have been no studies performed to investigate the blood flow features following fenestrated endovascular grafts. Thus, the purpose of this study was to investigate the changes in blood flow pattern, pressure and flow rates in patient-specific models of AAA after fenestrated stent graft implantation, based on our preliminary experience.

2. MATERIALS AND METHODS

2.1. Selection of sample patient data

Four patients with AAA unsuitable for conventional endovascular repair or open surgery were selected for inclusion in the study. These four patients had multislice CT (MSCT) scans performed before and after fenestrated stent grafting. MSCT datasets were obtained with a 64-detector row scanner with the following parameter: beam collimation 64x0.5, pitch 1.0, reconstruction interval of 0.5mm, 120 kV, 140 mAs. The fenestrated stent graft used in this study was Zenith AAA endovascular graft (William Cook, Brisbane, Australia). The type of fenestration implanted in our study involved small fenestrations (width and height: 6 x 6 mm or 6 x 8 mm) in the renal arteries, with scallop fenestration (width and height: 10 mm x 6-12 mm) planned in the superior mesenteric artery.

2.2. Selection of sample patient data

For generation of geometric aorta model, the first step is to segment the CT volume dataset with the aim of removing soft tissue, bony structures and other unwanted components, while keeping the abdominal aorta and its side branches (celiac axis, superior mesenteric artery, renal arteries, common iliac arteries). This was done semiautomatically using a commercially available software Analyze V 7.0 (AnalyzeDirect, Inc., Lenexa, KS, USA). The segmentation started 3cm above the celiac axis and the proximal part included celiac axis, superior mesenteric artery (SMA), bilateral renal arteries, while the distal part included common iliac arteries. For post-fenestration, stent wires were segmented for inclusion in the volume data, in addition to inclusion of the above mentioned aortic branches.

Following segmentation of volume data, an unstructured surface mesh of triangles was built over the segmented volume using the marching cube algorithm. The geometric information was saved in the 'STL (stereolithography)', a common format for computed aided design and rapid prototyping. The 'STL' file was converted into the CAD (computer aided design) model files using the CATIA V5 R18 (Dassault Systèmes, Inc., Suresnes Cedex, France). Figure 1 shows the segmented aorta model based on pre-and post-stent grafting MSCT data.

The aortic model mesh was defined by five prism layers using ANSYS ICEM CFD 11 (ANSYS, Inc., Canonsburg, PA, USA). ANSYS ICEM CFD provides sophisticated geometric acquisition, mesh definition and mesh editing which is important for the accurately flow analysis. Figure 2 demonstrates examples of AAA mesh model pre-and post-fenestrated stent grafting.

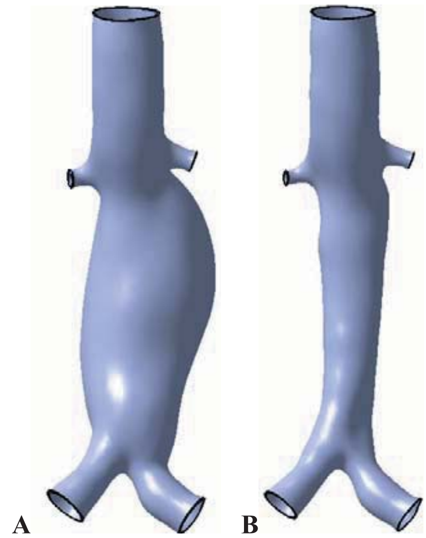


Figure 1. Geometric aorta model containing bilateral renal arteries, common iliac arteries and aneurysm pre (A) and post-stent graft implantation (B)

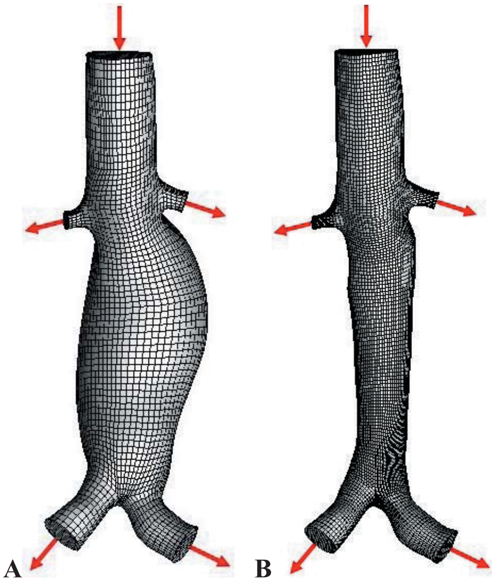


Figure 2. An aortic mesh model prior to (A) and post-stent graft implantation (B). Arrows point to the inlet and outlet of blood flow through the abdominal aorta and its branches.

2.3. Simulation of fenestrated vessel stents

According to our previous experience, the fenestrated vessel stents inserted into the aortic branches were demonstrated as an intra-aortic protrusion with a normal length of between 3-7 mm [8]. Therefore, we simulated the intraluminal protrusion of fenestrated stents at the renal arteries so that our analysis could reflect the real patient treatment. This was performed by adding simulated metal wires with circular appearance at the renal artery ostium as shown in Fig 3.

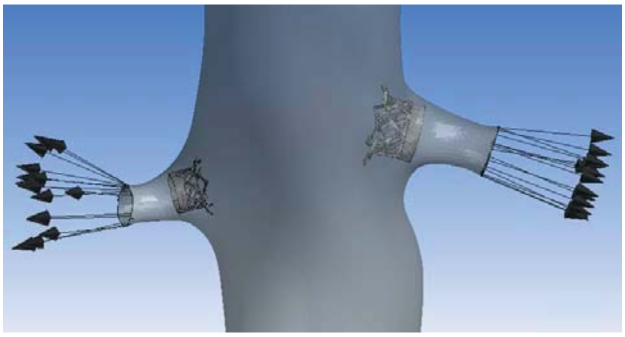


Figure 3. Simulation of fenestrated renal stents (circular appearance at the renal arteries).

2.4. Selection of sample patient data

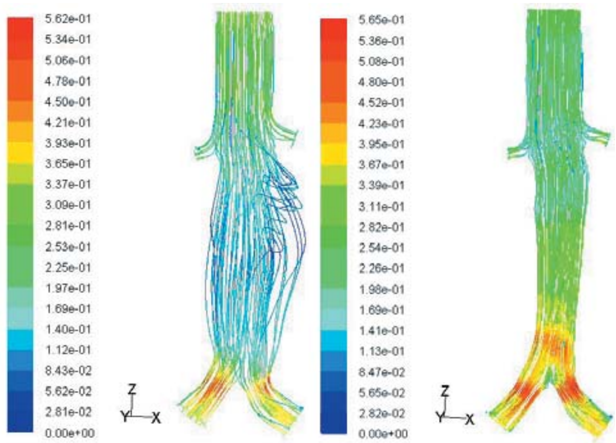
Normal physiological hemodynamic conditions have been considered for the 3D numerical simulations so that the flow analysis can be performed in a more realistic environment. In the present study, we compared the flow rate at the aorta model containing the four arterial branches, namely bilateral renal arteries and to the level of aortic bifurcation (common iliac arteries) prior to and after stent graft implantation. The fluid and materials properties for different entities were referenced from a previous study [12]. The main procedures in the performance of CFD analysis included the following steps:

1) Loading the hexahedral volume meshes;
2) Adding blood characteristics to the model. This step involves creation of the Newtonian fluid properties which include blood viscosity and density;
3) Adding physical properties including turbulence to the model using RNG k-epsilon model. The RNG model was developed using Re-Normalization Group (RNG) methods to renormalize the Navier-Stokes equations to account for the effects of smaller scales of motion. It performs better than standard k-model for more complex shear flows, and flows with high strain rates and separation;
4) Adding velocity at one inlet and four outlets, as shown in the following:
    a. Abdominal aorta at the level of celiac axis (inlet pressure) = 11220 (N/m^2)
    b. Left renal artery (outlet pressure) = 11170 (N/m^2)
    c. Right renal artery (outlet pressure) =11170 (N/m^2)
    d. Left common iliac artery (outlet pressure) =11120 (N/m^2)
    e. Right common iliac artery (outlet pressure) =11120 (N/m^2)
5) Computing the CFD analysis in terms of flow pattern, flow rate, velocity pathlines, wall pressure, wall shear stress.

Based on the above parameters, the blood flow was simulated at different cardiac phases (systolic and diastolic cycles) and measured in the aortic aneurysm, renal arteries and common iliac arteries pre-and post-stent graft implantation using the Fluent 6.3 (Fluent, Inc., Lebanon, NH, USA). Regarding the flow rate at these aortic branches, measurements were performed at proximal, middle and distal parts of each artery branch to detect any flow changes after fenestration. Blood flow pattern, wall pressure, and wall shear stress before and after stent-graft implantation were visualized and compared.

3. RESULTS

The general flow patterns generated in the rigid AAA models were in agreement with the literature [12, 13]. The changes of aortic flow pattern were noted with placement of fenestrated stent grafts. With deployment of the stent graft, flow disturbances began to occur less apparent within the aneurysm sac and vortices were less distinguishable. Figure 4 is an example showing the change of flow turbulence in a patient treated with a fenestrated stent graft. The blood flow became more smooth and laminar after fenestration as shown in Fig 4B when compared to the turbulent appearance observed at pre-fenestration in Fig 4A. The flow rate was significantly increased (more than twice) inside the aortic aneurysm when compared to that measured at pre-fenestrated stent grafting. This indicates that the blood flows through the new conduit formed by the stent graft instead of the widened aneurysm. While in the beginning of the abdominal aorta, approximately at the level of celiac or superior mesenteric artery, no significant change of the flow rate was noticed.



A B

Figure 4. Demonstrates that flow pattern observed pre- and post-fenestration. The blood flow became more smooth and laminar following fenestrated endovascular repair (B) when compared to the turbulent appearance observed in pre-fenestration (A).

For most of the measurements at the location of renal artery, the flow rate increased significantly following fenestration, and this is especially apparent at the systolic phase as shown in Fig 5. For flow rate measured at the common iliac arteries, a slightly increase was noticed without reaching significant difference.

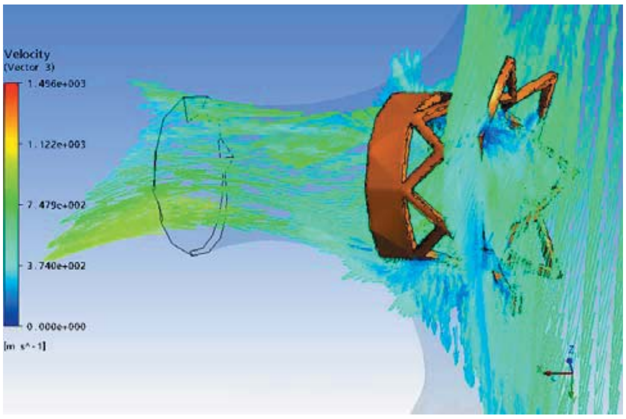
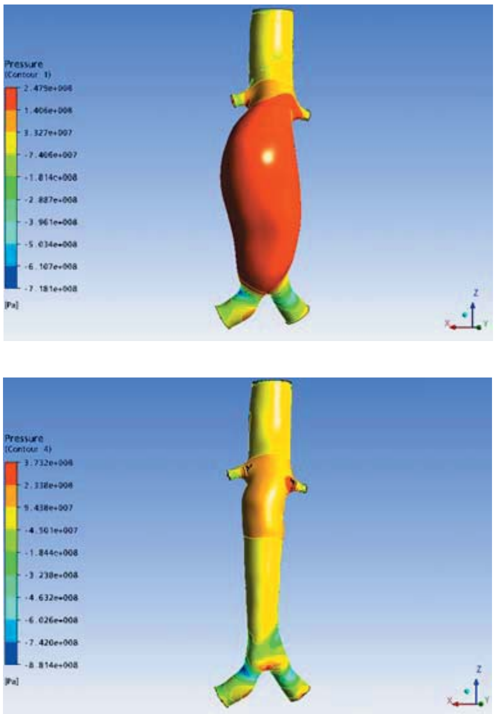


Figure 5. Shows the turbulence of blood flow at the renal artery due to presence of the fenestrated stent.

Change of wall pressure following implantation of a fenestrated stent graft was observed in the experiment, as shown in Figure 6. It is shown that the high pressure was seen within the aneurysm sac prior to fenestration. After implantation of the stent-graft, the maximum pressure is much lower inside the aneurysm sac.

A

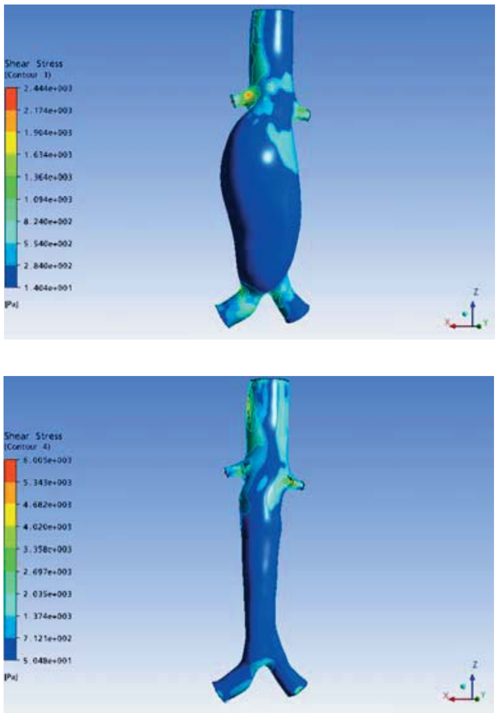


B

Figure 6. Prior to stent graft implantation (A), the wall pressure was higher than that observed in post-stent grafting (B), indicating the smooth blood flow inside the stent graft, which serves as a new conduit.

The areas of high wall shear stress are mainly situated in regions of enhanced recirculation or vortices. This is apparently observed in the level of renal arteries because of the vortices caused by the fenestrated renal stents which were implanted in the small fenestrations. After stent-graft implantation, there is no significant drop in maximum shear stress [Fig 7]. An area of high shear stress was found at the renal arteries, which is most likely to be caused by the presence of stent wires inserted into the renal artery branches.

A



B

Figure 7. Shows the wall shear stress noticed in pre- (A) and post-stent graft placement (B). It is seen in Fig B that no apparent change was noticed inside the aneurysm, and a higher shear stress is noticed towards the renal arteries and common iliac arteries.

4. DISCUSSION

This study is a first step in the investigation of the effect of fenestrated vessel stents on aortic side branches in patients treated with fenestrated endovascular grafts. Although based only on a small number of cases, our results provide a basis for testing the effect of placing a fenestrated vessel stent across the aortic artery branch, and research findings provide insight into the treatment outcomes of fenestrated endovascular repair.

The purpose of implantation of a stent-graft is to exclude the aneurysm from blood circulation so that the aneurysm gradually shrinks and becomes smaller while the blood flows through the new conduit, which is produced by the stent graft. Implantation of a stent-graft for treatment of AAA has undergone a series of technical modifications, and fenestrated endovascular grafting is the latest technical development which is designed to treat patients with complicated or suboptimal aneurysm necks. One of the main differences between fenestrated endovascular repair and traditional endovascular repair lies in placement of stent grafts across the visceral arteries while maintaining perfusion to target organs. Another difference is the insertion of stents to support and fix the fenestrated vessels, mainly the renal arteries. In addition, a stent normally protrudes into the aortic lumen by ~7 mm, as observed in our previous studies [8, 14]. Therefore, there are concerns about the safety and patency of fenestrated vessel stents or interference of blood flow by stent wires. This was observed in our study as there is significant increase of the flow rate measured at the renal arteries following implantation of fenestrated stents.

The deployment of a complex multi-component endovascular device in the abdominal aorta is likely to alter the local hemodynamics and adversely affects the long-term performance of the device. Previous research has been performed to study the fluid-stent graft interaction based on AAA models, however, these studies were focused on situations of infrarenally or suprarenally fixation of stent grafts [10-13]. Investigation of the flow analysis in the situation of fenestrated endovascular repair is an area which has not been studied before.

In our study, realistic AAA models generated from patients treated with fenestrated stent grafts were used to simulate the blood flow patterns and velocity changes. Our results are consistent to previous findings with regard to the velocity magnitude, wall pressure and shear stress changes following implantation of a stent-graft [10-13]. Specifically, our experimental results showed that flow changes were observed inside the aortic aneurysm after fenestrated endovascular repair, and this is mainly due to the blood flow through a narrowed conduit rather than the aneurysm.

One of the important findings in this study is that the flow disturbance was noticed to be significant at the renal arteries due to the effect of fenestrated vessel stents on the renal arteries. It is a routine procedure to fenestrate the renal arteries with insertion of the renal stents. Moreover, a proportion of the stents (<7 mm) is normally left inside the abdominal aorta. With stent wires protruding into the aorta, it is possible that material may adhere to the wires and thus affect the flow of blood into the renal arteries. We did not perform hemodynamic analysis by simulating the build-up materials on the stent wires in the current study. Experiments simulating the adhesion of materials on stent wires with regard to subsequent change of renal blood flow deserve to be performed.

Another important finding is the reduction of the wall pressure inside the aneurysm sac, as is the real purpose of stent-graft implantation, excluding from the pulsatile blood flow. This pressure is not zero, even if the sac is completely excluded from the stent-graft. The result corresponds to the findings of others [12, 15] and reflects the complex fluid-structure interactions between the blood flow and stent.

Previous studies of suprarenal fixation of stent grafts showed that the renal blood flow was not significantly affected when there is presence of stent wires in front of the renal artery ostium [16]. Variable configuration of suprarenal stent wires crossing the renal artery ostium was noticed, and the effect of stent wires on the renal artery ostium in terms of percentage decrease in flow rate was different, although not significantly. Similarly, with aid of 3D visualization, we are able to characterize the intraluminal appearance of fenestrated vessel stents in relation to the renal artery ostium, as shown in our early studies [8]. Thus, we would expect that the interference with blood flow patterns is variable depending on the type of fenestration or the length of stent protrusion. However, this was not investigated in the current study, which is one of the main limitations of our study. We only simulated the most common configuration of circular appearance of fenestrated stents in the current study.

Another limitation of this study is that the flow analysis was based on a rigid aorta model. However, the aorta or aneurysm is elastic and demonstrates pulsatile feature in real patients. Thus, further studies on patient-specific models by taking into account the above factors are essential to validate our results. Finally, a lack of correlation of 3D intraluminal appearance of fenestration with the corresponding flow analysis was not performed, and this needs further investigation.

In conclusion, our preliminary study showed a successful simulation of blood flow characteristics in realistic aortic models generated with patients treated with fenestrated endovascular grafts. Our results demonstrated that the disturbance of blood flow to renal arteries was significant following fenestration, although further studies are warranted to validate our findings. As fenestrated stent-graft repair of AAA is still in its infancy, and long-term outcomes of this technique are not fully understood, we believe investigation of hemodynamics will enhance our understanding of the effect of fenestrated vessel stents on blood flow features, which could be useful for assessing subsequent patency of fenestrated branches and renal function. A further analysis of the hemodynamic changes corresponding with the type of fenestration deserves to be investigated.

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