COMPUTATIONAL SIMULATION OF RESPIRATION-INDUCED DEFORMATION OF RENAL ARTERIES IN AAA PATIENTS AFTER EVAR

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Abstract

Introduction

During human respiration, the diaphragm contraction and relaxation induce renal artery displacement. Studies reporting cranio-caudal kidney motion show changes in curvature and branching angles associated with respiration (1), which for patients with an Abdominal Aortic Aneurysm (AAA) may affect hemodynamics and stent-graft placement. AAA is a pathological dilation of the lower section of the aorta. It is predominantly treated by endovascular aneurysm repair (EVAR), a minimally invasive intervention that consists of stent-graft (SG) insertion inside the aorta to restore the original aortic lumen, preventing blood flow from entering the AAA. Although numerical simulations of SG deployment in patient-specific cases of AAA have been performed extensively (2), only Tran et al. and Cheng et al. evaluated the respiration-induced changes in branch vessels for patients undergoing EVAR (3) (4).

The bending of the renal arteries can affect renal stenting and induce complications like stenosis and occlusions. However, no studies have numerically simulated renal artery movement due to breathing and its impact on SG deployment. Moreover, the choice of the SG length is a complex decision for surgeons; too short and it increases the risk of endoleaks, whereas too long and it increases the risk of occlusion. Therefore, it is essential to provide quantitative evidence to assist surgeons in choosing the optimal length. Furthermore, to have a complete perspective of the possible complications that may occur, even long-term after surgery, hemodynamics in the peripheral arteries needs to be monitored, with a particular focus on the renal arteries, to detect potential thrombogenic flow patterns. CFD studies can assess hemodynamic changes both post-operatively and over the respiratory cycle. Some CFD studies have demonstrated changes in renal artery flow post-EVAR. However, the actual post-operative peripheral stent-graft geometry was not simulated and they did not account for the impact of breathing. Consequently, the primary objective of this study is to address missing artery and stent-graft motion on the evaluation of changes in SGs deployment

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across three different stent-graft lengths for each artery. Additionally, the goal is to combine the outcomes of SG deployment simulations with CFD analyses of hemodynamic changes in the renal arteries, before and after EVAR, including motion throughout the respiratory cycle.

Methods

Two models from CT scans of the same AAA patient with acquisition in inspiration and expiration were segmented and meshed with 0.5 mm triangular shell elements. First, the breathing effect was numerically simulated in the pre-operative geometry, by applying a displacement at the distal extremities of the renal arteries, according to the kidney movements measured from the CT scans. The anisotropic Holzapfel-Gasser-Ogden model was used for the arteries. Then, a model of a peripheral SG was designed. 3-Point bending tests were carried out experimentally on SG samples and modeled numerically to characterize the SG mechanical properties. After the aortic SG insertion that followed the process described by Perrin et al. (5), peripheral SGs were collapsed into the catheter caliber, expanded with a balloon (modelled as a cylindrical shell), and released inside the renal arteries. To validate simulations of breathing-induced motion, vessel centerlines were extracted and compared to the variation in branching angle and maximum curvature from in vivo results reported in the literature (1). In order to validate the SG deployment simulations, the renal arteries' centerlines were extracted and compared with those of the lumen of the arteries from post-EVAR CT scans. Simulations were then repeated for longer and shorter SGs. To conduct CFD simulations, a velocity waveform was imposed at the inlet of the model (supra-celiac aorta). 2-element Windkessel boundary conditions were applied at the outlets, with the simulation conducted over five cardiac cycles (5 s). To more accurately replicate the hemodynamics of the renal arteries, artery motion was implemented to achieve respiratory movement of the renal arteries throughout a 5-second cycle (12 breathes per minute).

Results

By implementing a numerical model of the 3-point bending test, it was possible to replicate in silico the mechanical properties of the graft observed experimentally, solving an inverse problem. Peripheral SG were deployed in the renal arteries of two patients with the same length and diameter as the devices used clinically by surgeons. By comparing the centerlines of the four renal arteries at the end of the simulation with the ones from post-EVAR CT scans, mean distances below the imposed threshold (3 mm) were found for all of the arteries (1.59 mm, 2.79 mm, 2.57 mm, 1.99 mm), confirming the accuracy of the simulations.

Further calculations of the branching angle of the arteries revealed that the presence of the peripheral stent-graft reduces renal artery movement during the respiratory cycle, resulting in reduced variation in the branching angle. This effect is further emphasized when a stent-graft longer than nominal length is deployed in the renal arteries.

Moreover, preliminary CFD simulation results indicate a decrease in renal artery flow during the inspiratory phase due to the morphological changes, and a reduction in wall shear stress in the regions proximal to the maximum curvature of the vessel during the expiration, compared to the inspiratory configuration.

Discussion

In summary, we simulated the bending behavior of renal stents for the first time and were able to predict their deformation during breathing. Renal stenting with different SG lengths has been explored in patient-specific models to understand the effect of SG lengths and patient variability. Preliminary CFD studies have been carried out to assess the hemodynamic changes over the respiratory cycle. Future work includes CFD simulations in post-EVAR geometries to evaluate the impact of the stent-grafts, combined with breathing, on blood flow.

References

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