Multi-scale Biomechanical Modeling and Energy Loss Evaluation of Aortic Aneurysm

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Introduction

Aortic aneurysm (AA) may cause aortic rupture or dissection normally resulting in a sudden death. A prophylactic surgical intervention such as aortic replacement or endovascular stenting in an appropriate timing is mandatory. Currently, a surgical indication mainly depends upon the size of the aorta [1] whereas morphological features and physiological conditions are usually diverse in each patient and hence the risk for the aortic rupture or dissection must be distinguished from each other depending upon the patient's hemodynamic characteristics. It is known that there exist yet no effective methods being capable to quantitatively predict and evaluate the surgical treatments. Therefore, the development of a patient-specific model is of great importance for a purpose of predictive medicine, in which a goal should be accomplished in evaluating both morphological and physiological features locally and globally [2, 3] while considering their interactions.

Recent advances in biomechanics, medical imaging, computational methods and computational power have great potential and promise to revolutionize our understanding and thus treatment of cardiovascular diseases and there is a pressing need to synthesize these advances into a consistent and robust clinically useful tool [4]. In this study we propose a new approach on the patient-specific modeling of aortic aneurysms by combining a simulation-based multi-scale biomechanical model of the cardiovascular system (CVS) and a novel method in evaluating aortic energy loss. Our goal is to establish a clinically useful tool to enable a simulation-based prediction and evaluation of the AA surgery. A brief description of the methodology is first provided. Then application to the surgical operation of a 54-year-old man diagnosed with multiple aortic aneurysms is described and discussed, which demonstrates that the present approach is of great potential to effectively predict and evaluate the clinical treatments associated with aortic aneurysms.

Methods

Multi-scale computational modeling **-** A multi-scale computational model that combines a closed-loop 0D-1D model for the human cardiovascular system (CVS) with a three-dimensional, image-based, computational biomechanical model is established for quantitatively evaluating the aortic aneurysm (AA) hemodynamics. As illustrated in Fig. 1(a), the closed-loop CVS model is able to account for the phenomena of interest while incurring acceptable computational cost and is accomplished by multi-scale modeling. The arterial tree is described by a 1-D model while the remainder is described by a 0-D model, i.e., the lumped-parameter model. The two models are then coupled at the numerical level to yield a unique closed-loop system. The arterial tree consisting of the 55 largest arteries is described by a 1-D model (right), while the remainder, including the heart, the peripheral circulation and the pulmonary circulation, is represented by a lumped parameter model (left). As shown in Fig. 1(b) a lumped parameter element network of a vascular system corresponds to a peripheral artery: the network consists of several serially arranged compartments including the arteriolar, capillary, venular, and venous compartments (from right to left) [3].

The 3D aortic aneurysm model in Fig. 1(c) is constructed based on the 16-layer computed tomography (CT) scan images of a 54-year old male patient who was diagnosed with multiple aortic aneurysms in the descending aorta of 60 mm in size and the abdominal aorta of 48 mm. Three models are constructed corresponding with the cases of the pre-operation, the 1st operation for the abdominal aortic aneurysm, and the 2nd surgery for the thoracic aortic aneurysm. In the present multi-scale modeling approach the physiological conditions for the 3D multi-scale AA model are given based on the results of the 0D-1D CVS model and are assigned in terms of the computed flow-rate waveforms at inlet (at the base of aortic arch) and outlets of the 3D AA model (Fig. 1(d)).

An approach of energy loss evaluation - Methods in evaluating power or energy loss in arteries, in particular in relating to the prediction of the aortic AA rupture or dissection, are mostly associated with wall shear stresses because clinical decisions to intervene are based primarily on lesion size and such hemodynamic factors affect both the rate of the enlargement and rupture-potential. Aiming at establishing a clinically useful tool to predict and evaluate the post-operation performance of the AA surgery, we here propose a new approach to directly evaluate the energy loss by introducing two indices so as to asses how the aortic hemodynamic function is improved after the AA operations.

With consideration of the pulsatile blood flow in large arteries that is of features of peaking and steepening in pressure and friction-based reduction in velocity, we hereby propose a novel method by introducing two novel indices of a Pulsatile Pressure Index (PPI) to evaluate the oscillatory of the time-varying pressure-based powers, and a Pulsatile Energy Loss Index (PELI) to evaluate the power loss between the inlet and outlet of the artery of interest. The two indices are defined as follows:

$$PPI = \frac{1}{2}\left[1 - \frac{\hat{p}_A}{\hat{\hat{p}}_A}\right], \quad PELI = 2\left[PPI_{A\_outlet} - PPI_{A\_inlet}\right]$$

, where

$$P_A = \int_A p(\mathbf{V} \bullet n_A)dA, \quad \overline{P}_A = \frac{1}{T}\int_0^T P_A dt, \quad \overline{\overline{P}}_A = \frac{1}{T}\int_0^T |P_A| dt,$$

$$Q_A^t = \int_A (\mathbf{V} \bullet n_A)dA, \quad Q_{A\max} = Max(Q_A^t),$$

$$\hat{p}_A = \frac{\overline{P}_A}{Q_{A\max}}, \quad \hat{\hat{p}}_A = \frac{\overline{\overline{P}}_A}{Q_{A\max}}.$$

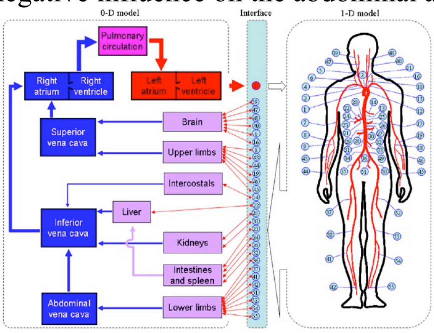
Here *p*, *V, A,* and *Q* represent the pressure, velocity, cross-sectional area and flow-rate at a specific location in a blood vessel, respectively.

Results

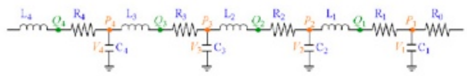
A 54-year-old male patient with aneurysms of both descending and abdominal aorta (60 mm and 48 mm, respectively) was selected for study. In staged procedures, the abdominal aneurysm was first replaced with a 30 mm Hemashield straight graft, while the descending aorta was repaired two weeks later, using another 30 mm Hemashield straight graft under cardiopulmonary bypass (left femoral artery/vein and left axillary artery cannulated). Patient recovery was uneventful.

The oscillatory shear index (OSI) that represents the average value for one cardiac cycle is plotted in Fig. 1(c). It is seen that the OSIs are initially elevated in descending aorta and at the hinge point, where the aorta intermingles with diaphragm and vertebral column. Following surgery, the OSIs in ascending aorta declined from slightly above 0.35 to nearly 0.30, while the OSIs in infrarenal abdominal aorta remained high. The average OSI of the entire aorta is also calculated, showing a mean OSI of 0.280 before the operation, but a significant reduction after the 1st and 2nd surgeries down to 0.257 and 0.221, respectively. The OSIs shows the largest value at the aneurysmal site in the descending aorta with a magnitude of 0.415 before the operation, whereas the mean OSI is reduced from 0.280 to 0.257 after the 1st operation, and 0.221 after the 2nd operation.

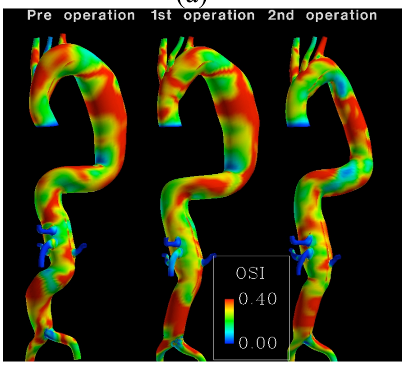
Furthermore, the averaged PPI shows a significant reduction from 0.445 before the surgery to 0.423 after the 1st operation, and further down to 0.359 after the 2nd operation, whereas the PELI shows a remarkable drop from 0.986 to 0.820 after the 1st operation and to 0.831 after the 2nd operation. Our results indicate that the aortic aneurysm deteriorates efficient blood delivery system resulting in significant energy loss, which is consequently ameliorated by the grafting procedures (the two surgical operations). The cause of the slight rise in PELI after the 2nd operation is not clear but may be due to the occurrence of a complex vortex flow structure, which is observed at the portion of the abdominal aorta after the 2nd operation. This implies that the 2nd operation on the descending AA may extend somehow negative influence on the abdominal aortic hemodynamics.



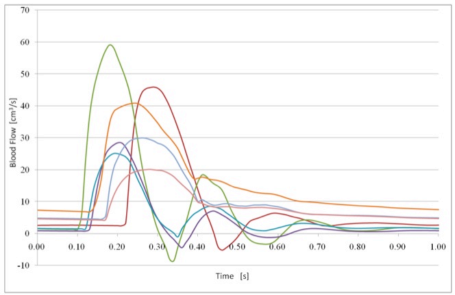
(a)



(b)



(c)



(d)

Fig. 1 (a) Schematic description of 0D-1D multi-scale modeling of the human cardiovascular system, (b) a lumped parameter element network of a vascular system corresponding to a peripheral artery, (c) a n image-based 3D aortic aneurysm model with OSI distributions, and (d) flow-rate waveforms at inlet and outlets.

Conclusions

In this study, we propose a new approach on patient-specific modeling of the aortic aneurysms by combining a multi-scale computational biomechanical model of the cardiovascular system (CVS) and a novel method in evaluating aortic energy loss. Application to the surgical operation of a 54-year-old man diagnosed with multiple aortic aneurysms indicates that the present approach is of great potential to effectively predict and evaluate the clinical treatments associated with aortic aneurysms.

Acknowledgment

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