INFLUENCES OF NONPLANARITY, BIFURCATIONS, DYNAMICS, INFLOW AND OUTFLOWS ON BLOOD FLOW PATTERNS IN AORTIC ARCH: A MULTI-SCALE COMPUTATIONAL STUDY

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INTRODUCTION

The human aorta is the major blood vessel transporting blood pumped by the left ventricle to the systemic circulation. The aortic arch has complicated geometry including non-planar curvatures in three-dimensions, branches at the apex of the arch, significant tapering with distensible vessel walls; and it even shows dynamic movements in particular in ascending aorta. The cyclic nature of the left ventricle also creates strong pulsation in the aortic arch as well as in other arteries. It has been reported that localization of atherosclerotic plaques are well observed at the inner wall of the aortic arch and in the region of branch vessels and bifurcation in the descending aorta as well as in the carotid vessels, which shows strong correlation with blood flow patterns. The *in vivo* studies show complicated three-dimensional flow development in the aorta in which helical and retrograde flow patterns are consistent features of intra-aortic flow [1]. Many theoretical, *in vitro*, and computational studies of aorta hemodynamics have been performed but with specific emphasis either on nonplanarity in aorta geometry, or on inflow condition, or on vessel dynamics [2] and the aorta hemodynamics still remain not very clear yet.

In this work we aim to establish an image-based, multi-scale, computational modeling of blood flow in the aortic arch and to make a comprehensive understanding of the aorta hemodynamics with consideration of influences of geometric nonplanarity and bifurcations, vessel dynamics, pulsatile inflow and outflow boundary conditions. The ultimate goal is to clarify the correlation between the blood flow patterns and the incidence of aorta aneurysms.

METHODS

As a prototype multi-scale hemodynamic model we have developed a multi-scale, computational method [3] that is able to predict blood flow and pressure in the systematic arteries at any position along the vessels and to compute local flow patterns as well as wall shear stresses at any point in any vessel or organ. A one-dimensional model is established on a basis of the axisymmetric Navier-Stokes equations for flow and pressure propagation in compliant and tapering vessels. The three-dimensional model is utilized for specific vessel or organ, which is an in-house solver for the full Navier-Stokes equations and is embedded into the one-dimensional network model for the systematic arteries. In this prototype multi-scale computational model, we are aiming at establishing an interactive model in which, not only the global one-dimensional model can provide boundary conditions for the local three-dimensional model in terms of flow rate q and pressure p, but also that the three-dimensional model with realistic geometry can be used to improve the one-dimensional model in terms of feedback of the detailed flow information such as pressure drop.

An image-based, realistic anatomic geometry of the aortic arch with bifurcations and taper as well as vessel dynamics is constructed based on the X-ray CT images as illustrated in Fig. 1. The magnetic resonance measurement of inflow waveform at the Asc. aorta is utilized and the profiles of outflow at the Dsc. aorta, the Anonyma artery, the L. Carotid artery, and the L. Subclavian artery are all defined based on the prediction of the one-dimensional model. At inlet to the arterial tree, i.e., the Asc. aorta, the flow profile is directly imposed at the boundary with a uniform flow over the cross-section; but at each outlet three-dimensional velocity profiles are determined on a basis of the predicted flow profiles in a manner of Womersley solution and are imposed at the end of a virtual outlet region connecting to the real outlet boundary.

RESULTS

A series of stepwise computations of blood flows in the prototype aortic arch model have been conducted with specific focus on the influence of nonplanarity, bifurcations, dynamics, inflow and outflows on the aorta hemodynamics.

Given the reference length of the diameter at Asc. aorta, 2.5cm, the top speed based on the maximum flow rate at the Asc. Aorta of approximately 87.6cm/s, the beating period of about 1.1s, the density of 1.055 g.cm3, and the viscosity of 0.049 g/(cm3) [4], we calculated a maximum Reynolds number of 4700 and a Womersley number of 14.0 that corresponds to a Strouhal number of 0.026. The turbulence model is disregarded in this computation and the fluid is assumed to be laminar throughout the complete beating cycle. Fig. 3 and Fig. 4 show the blood flow patterns at a. Early systole and b. Mid-systole in a form of velocity vectors and pressure contours in the aorta models without (Fig. 3) and with (Fig. 4) vessel dynamic influence, respectively. The color map denotes the pressure increasing from blue to red. Overall, this comprehensive study indicates the following characteristics of blood flow development in the aorta: 1) the non-planarity in geometry can result in the helical flow but only when the core stream flows over the apex of the aortic arch; 2) the bifurcations create strong skewed helical flows in the Anonyma artery, the L. Carotid artery, and the L. Subclavian artery and also lead to complicated separated regions in the aorta in particular at diastole; 3) the vessel dynamics can create and enhance the helical flow in the Asc. aorta (Fig. 3 and Fig. 4) at early-to-mid-systole; 3) the secondary flow at inlet can extend its influence on the blood flow throughout the aorta; and 4) the 1D model-based outflow boundary conditions are physiologically adequate and important which show remarked discrepancy compared with the conventional boundary conditions as zero gradients for pressure and/or velocity at outlet.

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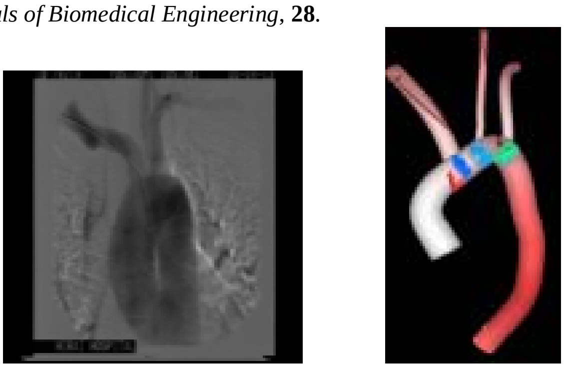


a. X-ray image b. Constructed geometric model

Fig. 1. A realistic geometric model of aortic arch

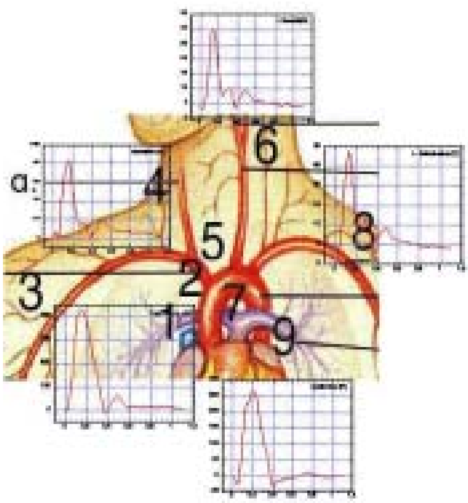
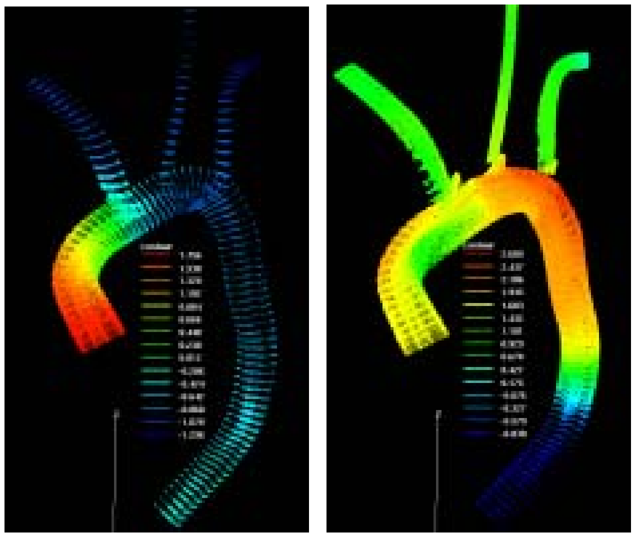


Fig. 2. 1D model-based inflow-and outflow waveforms

a. Early systole b. Mid systole

Fig. 3. Velocity vectors and pressure contours in the aortic arch without vessel dynamic influence



a. Early systole b. Mid systole

Fig. 4. Velocity vectors and pressure contours in the aortic arch with vessel dynamic influence