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Fluid–structure interaction within three-dimensional models of an idealized arterial wall

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ABSTRACT

The ascending branch of the aorta is one of the most stressed organ of the arterial system. We aim to design a biomechanical model for analysing the aorta dynamics under a shock. The model includes the aorta layers and the influence of the blood pressure. We undertake a three-dimensional modal analysis of the coupled aorta–blood system. We determine in the present work the coupled natural frequencies and the modes shapes of the system of the aorta and blood. Three models are presented in this study: three-layers model, two-layers model and one layer model. For the analytical solving a potential technique is used to obtain a general solution for an aorta domain. The finite element model is then validated by these original analytical solutions. The results from the proposed method are in good agreement with numerical solutions.

1. Introduction

Traumatic rupture of the thoracic aorta is commonly known as a fatal injury. The investigation and treatment of Blunt Traumatic Aortic Rupture (BTAR) or Blunt Traumatic Aortic Injury (BTAI) are nowadays well described. However, some uncertainty remains with regards of the pathogenic aetiology of BTAI. The injury and consequently the rupture are thought to be the result of both anatomic and mechanical factors. Initially, investigators proposed that BTAR was due to sudden increasing of arterial blood pressure. Later, recent theories suggest that injury or rupture result from a complex combination of mechanical stresses and is thus highly multi-parametric. Numerous factors are involved in the injury process but it remains uncertain to what extent, if any, each of them plays a part and under what circumstances. Of course, every mechanical force acting on the aorta may be important in the injury process (Zhao, Field, Diggers, & Richens, 2008). However, the relative importance of these forces still remains unclear and several different forces and hypotheses have been proposed over the years. It was thought that the injury was caused by a sudden stretching of the aorta. However, this mode of failure was probably not the only one since a cylindrical vessel under pressure would rupture axially rather than transversely. Then, some others attributed the occurrence of injury to a sudden increasing of blood pressure or also to the occurring of a water-hammer effect, which leads to high-pressure waves being reflected back along the vessel wall (Forman, Stacey, Evans, & Kent, 2008). Nevertheless, the water-hammer model is unable to consider the additional deformation of the aorta during an impact where increasing the curvature of the aorta could possibly lead to greater increases in the pressure wave in this region (Prosi, Perktold, Ding, & Friedman, 2004). More recent theories propose that aorta injury results from a

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combination of mechanisms including shear, torsion and stretching (Zhao et al., 2008). These loadings are coupled with the blood pressure and propagation of wave within the aorta. To this end, it seems necessary to include the blood and the vessel undergoing deformation and interacting with the blood flow (Moore et al., 2008). In sum, there are still no definitive answers as to what the fundamental mechanisms are that cause this injury, though a great deal of speculation exists on what these might be. However, the high level of reproducibility of the site and nature of blunt traumatic rupture intuitively suggests that there is a reproducible mechanism of injury.

The largest artery in the body is the aorta. The highest fluid pressure in the body is the systolic pressure of the blood as it exits the heart into the large arterial system. The minimum pressure of this same blood is the diastolic pressure of the end of the heart's pumping cycle. The blood pressure in various parts of the body is also affected by accelerations of the body. The biomechanics within the ascending aorta characterizes the pressure and flow for the entire vascular system (see Fig. 1). One of the most stressed parts of the entire vascular system is the ascending branch of the aorta. Indeed, this branch is the first part of the system receiving the blood from the heart at the opening of the aortic valve, during the systolic phase. The study and the understanding of the dynamics of this branch is rather complicated due to the coupling effects and due to the heterogeneity of the organ radially.

The goal of this paper is to analyse the influence of the blood–aorta interaction on the coupled natural frequencies. Analytical method, based on the modal decomposition, and numerical method, based on the finite element method. We deal with modal analysis of the aorta with and without fluid (blood). For that purpose, analytical solutions of the coupled problem are obtained conversely to previous results (Zhang, 2002; Zhang, Liu, & Lam, 2001). Then the sensitivity of these natural frequencies and modal shapes is investigated with regards of the layers distribution. Wall properties are those used by Gao, Guo, Sakamoto, and Matsuzawa (2006). Solving the equation is based on the Helmholtz decomposition (Morse & Feshbach, 1946) of the wall displacement. This allows us to write the overall equation in terms of potentials. We assume an inertial coupling meaning that the longitudinal wave celerity is greater than any characteristic velocity of the blood flow. The blood is assumed compressible. One layer case, two layers case and three layers case are compared. Numerical solutions are compared with analytical results for assessing the reliability of the FEM software.

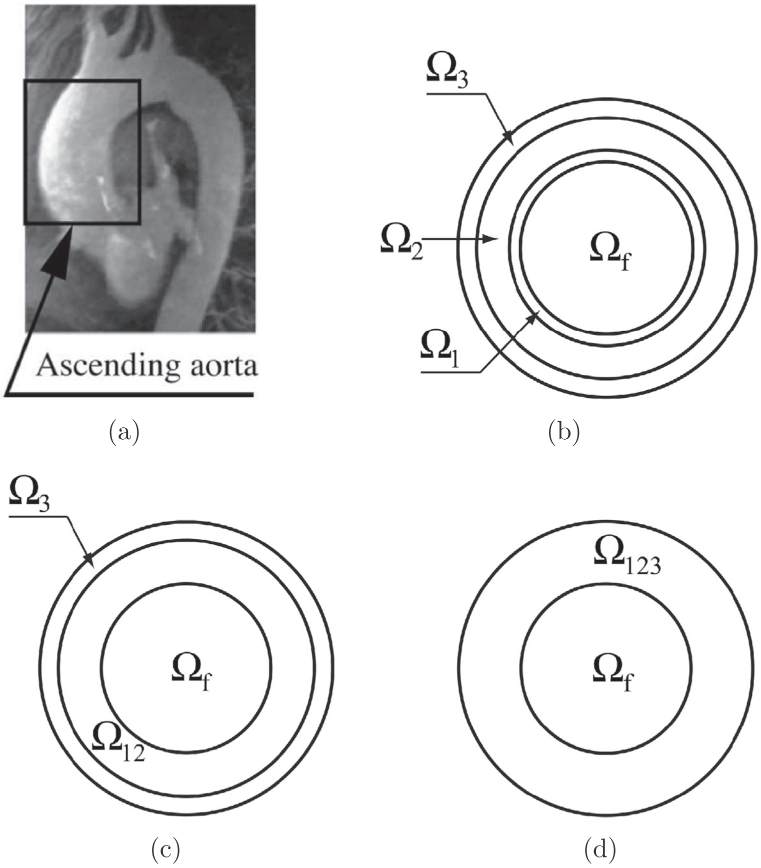

Fig. 1. Ascending aorta and its multi-layers cross sectional model: blood Ω_f, intima Ω_1, media Ω_2, adventitia Ω_3. (b) Three-layers model, (c) two-layers model and (d) one-layer model.