

Preface

Traditionally, cardiovascular studies have been limited to medical textbooks and courses, taught by medical experts. Now, computational modeling and simulation has infiltrated the medical field which has advanced to a point where it can be categorized into its own sub fields. The use of Computational Fluid Dynamics (CFD) for modeling cardiovascular flow leads to a new field of study known as computational biomedical engineering. In particular when we model blood as a biofluid and compute its flow, we establish a branch termed as *Computational Haemodynamics* (CHD). This new field of engineering constitutes important knowledge in the study of blood flow mechanics, surgical and medical treatment, and design of biomedical devices. This has only been possible through the emergence of advanced technologies in medical imaging, and computers. Since the fundamental principles of CHD are based on CFD, these two terms are quite similar and used interchangeably in this book.

This book is designed to convey information pitched at an appropriate level of knowledge to new students with a diverse background of medicine, physiology, pharmaceutical science, mechanical engineering, and mathematics. This book cannot deliver the entire scope of knowledge that is related to cardiovascular modeling. Rather, it provides an important link between traditional engineering and computational fields with the medical field. For example, an undergraduate who is trained in engineering can selectively read the relevant chapters of the book that provides new knowledge on the computational simulation or medical aspects.

There is a diverse range of CFD books in the market are written with different levels of complexity. To ensure the reader is not overwhelmed by overly advanced mathematical notation and theory, this book describes fundamental mathematical ideas, coupled with sufficient description and backed up with examples. It is intuitive and systematically structured for enhancing the learning process and allowing students to be able to quickly use CFD practically. Nevertheless, a fundamental knowledge of calculus such as basic anti- and differentiation is still required prior to reading the book. With the hands on practice and reading, this book can enable CFD beginners to efficiently perform reliable CFD simulations for the CHD applications.

The book begins with Chap. 1, which prepares the reader for an overview of CHD, its advantages and disadvantages, a preliminary understanding of CHD, and

its numerous applications in the cardiovascular system. It aims to initiate curiosity and stimulate creativity for the reader to think of possible solutions to engineering problems related to cardiovascular flow.

In Chap. 2, the human cardiovascular system is presented concisely. By providing the description of the cardiovascular anatomy and physiology at an elementary level, this chapter is useful for readers that have previously not received any form of medical training. An understanding of the cardiovascular anatomy provides a basis for an accurate computational fluid flow setup for geometrical reconstruction based on medical imaging, definition of the relevant anatomical structures, and determining cardiovascular flow boundary conditions.

Medical image reconstruction of the cardiovascular anatomy is covered in Chap. 3, which introduces the reader to medical imaging, geometrical reconstruction, manufacturing or reverse engineering, and Computer-Aided Design (CAD). The book steps through all of the processes from medical image scanning (MRI or CT scans) through to segmentation, and leading to model reconstruction. Important features of each process with informative description of the approach used or available software are given in detail.

Chap. 4 presents the fundamentals of haemodynamics, firstly introducing the properties of blood and then its flow properties. Since blood flow is enclosed by the arterial walls, it is an example of the well-established internal pipe flow theory. This incorporates the laws of fluid dynamics and its interaction with solid surfaces. Characteristic flow features of blood flow in different regions of the circulatory system are presented to exemplify its behaviour.

In Chap. 5, the governing equations of fluid flow, i.e. the Navier-Stokes equations are introduced. Each term in the equations is described in such a way that the reader can appreciate its physical interpretation and impact on the flow. A brief introduction to turbulence and its modelling is also given, which is quite unusual for this type of book. However we feel that since cardiovascular flows through stenosed arteries and some medical devices will exhibit some form of turbulence, it is worth mentioning here. A summary of the different turbulence models is given with guidelines on setting up the different models. A derivation of the equations for solid dynamics is given with an emphasis on the elastic properties of arteries. The discretisation of the continuum equations for the fluid and solid dynamics onto discrete points in a computational domain are shown using the more well-known methods that include the Finite Difference, Finite Volume, and Finite Element Methods. These methods are solved algebraically using both direct and iterative methods. The coupling of the fluid and solid domains produce the Fluid-Structure-Interaction (FSI). This takes place at a shared interface where the fluid and solid meet. Force loadings and structural deformation results are passed from one analysis to the other and the coupling approaches are described. A major difficulty with FSI is the stability and convergence and these issues are discussed.

Description of mesh development for different anatomies are described in Chap. 6. The discretised equations from Chap. 5 are transferred to a corresponding *discrete* set of points in flow field where solutions of the flow variables such as the velocity, pressure, temperature, and deformation are performed. Both static

and fluid-structure-interaction meshing are presented. Generation of a quality mesh requires both a good sense of creativity and technical knowledge. Therefore, this chapter provides guidelines to the reader prior to delving into the interesting experiments of meshing different anatomical models. Different types of mesh and its setup for simplified and more advanced geometries are illustrated without presenting overly complicated mathematical algorithms. Furthermore guidelines and best practices are given for developing quality meshes and material presented will give the reader an introduction into mesh creation.

Having laid the groundwork to establish a strong theoretical base, Chap. 7 applies the foundational knowledge and putting them into practice through selected demonstrative applications. The entire process from scans to the final data analysis is shown. The examples include models of a stenosed carotid artery, patient specific carotid bifurcations, stented artery, and cardiac chamber. Post-processing techniques are presented which involves converting the raw data into graphical representations.

Computational simulations increase in complexity when it considers blood flow within elastic wall structures of the cardiovascular system. Chap. 8 presents some FSI cardiovascular applications to provide the reader with an overview of some developments in this emerging field. FSI is being used as a demonstration of practicality of achieving a higher physiological realism in haemodynamics analysis over simple rigid wall assumptions. Applications include atherosclerosis in carotid bifurcation, calcified plaque rupture, aortic aneurysm, as well as coronary artery bypass graft.

The book culminates with Chap. 9 that explores the future trends and more advanced modelling techniques. While the detailed treatment of these advanced techniques are beyond the scope of this book, it is hoped that the chapter will stimulate further enthusiasm in the advancing capability and innovative use of CFD and FEM for studies related to computational haemodynamics.

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