Politecnico di Torino, Doctoral Program in Electrical, Electronics and Telecommunications Engineering (XXXIV cycle).
Doctoral dissertation.

Boundary Conditions Estimation Techniques for Cardiovascular Modeling

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Dissertation Summary

Cardiovascular diseases are the leading cause of mortality worldwide, responsible for more than 17 million deaths every year. For this reason, the study of the cardiovascular system and of the mechanisms governing blood flow has attracted significant and increasing interest from both the medical and engineering communities. In this context, computational models of the cardiovascular system have been increasingly adopted for studying the role of blood flow in the development of cardiovascular diseases, and have proved useful for a number of tasks, including surgical planning, non-invasive diagnostics, and medical device evaluation.

In order to be safely and effectively used in real-life clinical scenarios, cardiovascular models need to be accurate and reliable. One of the biggest challenges is represented by the estimation of appropriate boundary conditions (BCs), which need to be imposed at the boundaries of the domain of interest, to provide a description of blood flow dynamics outside the model. Boundary conditions are essential to guarantee a unique solution to the system, and they are a crucial step in the creation of any computational model. Specifically, the estimation of boundary conditions needs to be *automated*, to facilitate the adoption of cardiovascular models in the clinic, *robust*, to ensure reproducibility and prevent inter- and intra-operator variability, and *patient-specific*, to personalize the model to the specific patient. Toward these goals, this thesis proposes a set of novel, automated, and robust techniques for the estimation of boundary conditions.

The thesis is organized into three main parts. In the first part, a *data and model-driven* approach is presented, where resistive boundary conditions are estimated by solving an optimal control problem. The choice of boundary conditions, in fact, is guided by an effective combination of patient-specific data and by a physical description of the underlying system, by means of the Stokes equations. The proposed method is tested on fully patient-specific cases, with anatomies reconstructed from CT images of the aortic arch, flow measurements coming from 4D-Flow MRI, and non-invasive pressure measurements.

The second part presents a novel framework for the automated estimation of higher order lumped parameter boundary conditions, by means of the time-domain vector fitting algorithm.

The purely *data-driven* nature of this approach leads to a fast and inexpensive estimation process, while enabling the adoption of more accurate boundary conditions of arbitrary complexity, in the form of black-box models.

In the last part of the dissertation, a numerical investigation of the minimum energy principle in patient-specific anatomies is conducted. In view of the limited availability of patient-specific measurements, BC estimation techniques which do not require in-vivo measurements, and are instead *physics and anatomy-based*, are particularly attractive. Among these, the minimum energy principle is often adopted in the form of Murray's law, for the selection of resistive outlet boundary conditions. The proposed investigation verifies if a minimum energy point also exists in realistic anatomies, if it can be identified numerically, and if it can be used as a possible criterion for inlet flow estimation.

In summary, this dissertation provides a set of novel techniques for the estimation of boundary conditions. Their validity is documented with relevant numerical examples, which prove the effectiveness of an increasingly automated, robust, and patient-specific approach to boundary conditions estimation.