Computational Hemodynamic Modeling of the Cardiovascular System

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ABSTRACT

Computational methods and modeling are widely used in many fields to study the dynamic behaviour of different phenomena. Currently, the use of these models is an accepted practice in the biomedical field. One of the most significant efforts in this direction is applied to the simulation and prediction of pathophysiological conditions that can affect different systems of the human body. In this work, the design and development of a computational model of the human cardiovascular system is proposed. The structure of the model has been built from a physiological base, considering some of the mechanisms associated to the cardiovascular system. Thus, the aim of the model is the prediction, heartbeat by heartbeat, of some hemodynamic variables from the cardiovascular system, in different pathophysiological cardiac situations. A modular approach to development of the model has been considered in order to include new knowledge that could force the model’s hemodynamic. The model has been validated comparing the results obtained with hemodynamic values published by other authors. The results show the usefulness and applicability of the model developed. Thus, different simulations of some cardiac pathologies and physical exercise situations are presented, together with the dynamic behaviors of the different variables considered in the model.

Keywords: Computational Modeling, Heart, Pulmonary Circulation, Systemic Circulation, Valvular Stenosis

1. INTRODUCTION

Cardiovascular diseases are one of the most common causes of death in the world, with an estimated 7.1 million deaths per year (Venkataraman et al., 2013). Notwithstanding the significant advances achieved in cardiology and the new diagnostic and treatment modalities, morbidity and mortality rates associated with cardiac pathologies still remain very high (Itu et al., 2012).

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Another aggravating fact of some cardiovascular diseases is the continuum of health care throughout the patient’s life. This contributes to a drastic increase in costs associated with this issue. These costs are estimated to be around 196 billion euros only in the European Union (Nichols, Townsend, Scarborough, & Rayner, 2012) and this trend will increase over the coming years. Thus, it is necessary to invest effort in researches that combine both technical studies and experimentation to expedite the introduction of new diagnostic procedures, modalities in patient monitoring and more effective therapies (Heldt, Mukkamala, Moody, & Mark, 2010).

Nowadays, the clinical management of patients is based on the prior experience of the medical staff, the clinical protocols for routine hospital practice, the knowledge derived from statistical population studies about patients samples with pathologies similar to the ones under study (Douali & Jaulent, 2013), and diagnostic methods, often invasive (Abbasi et al., 2013). This is why it is not known how reliably the patient will respond to the different pharmacological or surgical interventions.

The emergence of personalized medicine enables to adopt new practical methodologies in diagnosis using clinical parameters for personalized patient care (Douali & Jaulent, 2013). In this regard, new opportunities are being presented by personalized medicine in the treatment of cardiovascular diseases, considering specific factors for patients such as age, family background, co-morbidity, medication, genetic information or lifestyle among others (Johnson & Cavallari, 2013). New research lines emerging from technological advances in the last years, such as the use of 3D electrocardiograms (L. Zhang, Xie, Balluz, & Ge, 2012), magnetic resonance imaging (Glatz et al., 2012), anatomical and geometric characterizations (KrishnankuttyRema et al., 2008), medical image analysis (Hata et al., 2013), speedometers for microparticles or computational models (Lara et al., 2011), among others (Lara et al., 2011), allow a detailed and personalized monitoring and prediction concerning the patient evolution. The ultimate aim is to help to achieve a better diagnosis and the most suitable treatment for pathological conditions, increasing the patient’s life and improving the quality of life at large.

In this regard, computational modeling has been proven to be a useful resource for the analysis and comprehension of the complex biological mechanisms within the vascular system. It also helps to supplement other experimental studies to understand the cardiovascular pathophysiology and to generate biomedical and clinical knowledge.

Computational modeling is supposed to be an alternative to animal experimentation. Its usage is recommended by the VPH Institute (Hunter et al., 2013), which presents four potential benefits such as: reduction, refinement, replacement and translation. Modeling techniques are seen as the ultimate objective to minimize the number of animals used for experimental purposes replaced by predictions made by these models.

Others advantages of computational modeling are associated to their allowing the simulation in different pathophysiological conditions with a simple variation in the parameters described by the model. In general, the expected results can be evaluated almost instantly in current computers. Thus, a computational model can also serve as a previous monitoring tool to the animal testing and can provide a useful knowledge to the surgeon before performing a surgical intervention.

In this work, it is introduced the design and development of a computational model that simulates the different behaviors associated to some hemodynamic variables of the cardiovascular system from different pathophysiological cardiac conditions. The purpose of this model is to serve as a clinical tool helping to provide a better understanding of the pathophysiological behaviors of the cardiovascular system.

The remainder of this article is organized as follows. Related work is discussed briefly in Section 2; in Section 3, is described the structural model and the steps followed for the model construction; Section 4 contains a description of the experiments conducted by computer simu-
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