Clinical simulation of aortic valve: a narrative review

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Abstract

Introduction: About 30 percent of the worldwide death is due to cardiovascular diseases. Clinical simulation is a promising filed that can help to understand diseases, their nature and intervention’s effects. The simulated models are flexible and make it easy to study the changes’ effects and help to select the appropriate interventions. This narrative review aims to report common methods for the clinical simulation and its merits focusing on the cardiovascular field especially those pertaining to the aortic valve.

Method: The search was conducted on google scholar and PubMed in August and September of 2014 with three queries’ categories. We searched among English papers with no limitation on the published year. A qualitative–interpretive approach was used for data extraction.

Results: Computational fluid dynamic (CFD) is used to simulate and study body structures, systems and their common phenomena. Its two common methods for cardiovascular simulations are Finite Element Method (FEM) and Finite Volume Method (FVM). There were two kinds of the aortic valve simulation: dry models and Fluid–Structure Interaction (FSI) models. Unlike the dry model, FSI models consider the interaction between blood flow and tissue. Clinical simulation is a promising field allowing statistical analysis and can be used in clinical decision support systems (CDSS) or as a virtual experimental platform as a training system.

Keywords. Cardiovascular diseases, Aortic Valve, Computer Simulation, Finite Element Analysis

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Introduction

Although the exact figures of the worldwide cardiovascular diseases are not available, the World Health Organization have estimated about 30 percent of the world’s mortality to be caused by cardiovascular disease. Nowadays the change in lifestyle, physical inactivity, unhealthy diet, smoking, diabetes etc. have increased the cardiovascular diseases in all age groups [1].

A group of the cardiovascular diseases is related to the heart valves. The aortic valve is one of the four heart valves that guarantees the unidirectional blood flow ejection from the left ventricle to the whole body and is effective in the heart functioning and coronary blood flow [3]. If the repair of the defect valve is impossible, it will need to be replaced [2]. One of the therapy challenges is the estimation of the intervention’s effects. Knowing about the hemodynamic and mechanical factors of the diseases helps to understand them, their nature and intervention’s effects [10]. Clinical simulation is a promising filed that can facilitate gathering these kinds of information.

Simulation is a powerful increasingly used method and tool in medical informatics [5,6] that can be applied to eventually reduce the mortality and morbidity [7,8]. However its full potential needs to be discovered and demonstrated [8]. In medical informatics there are generally four classes of the simulation scope [8]. The scope of this article is clinical or medical simulation that is used to study, analyze, and replicate the function and behavior of the complicated body systems or diseases, structural and environmental changes’ effects and a variety of assumptions [8]. Compared to the common methods, it is cost-effective and needs lower time [5-7]. The results make the understanding of the physiological and pathological issues easier and help the physicians and surgeons to diagnose and design the appropriate therapy method based on numerical analyses [6,8]. Flexibility of the simulated models makes it easy to study the changes’ effects and facilitates the selection of the appropriate interventions [5,6,8,11].

This paper reports a narrative review of the clinical simulation and its potentials that focus on the cardiovascular field especially the aortic valve. To the authors’ knowledge there is no such broad review on this topic.

1. Methods

Our narrative review was performed according to Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [4] but considering a more narrative approach. We determined the search terms by defining our search questions and exploring for Medical Subject Heading (MeSH) terms. References were managed in Zotero. The search was performed on google scholar and PubMed in August and September of 2014 with the following queries’ categories:

1. Computer Simulation
2. Computational fluid dynamics OR Finite Element Analysis OR Finite volume Analysis
3. Cardiovascular system OR Aortic valve

Search results were limited to papers in English without any limitation for the published year. The titles and abstracts of the retrieved papers were manually screened. Papers with the following inclusion criteria were selected for the final analysis:
cardiovascular computational fluid dynamic simulation and finite element or finite volume simulation of the aortic valve having clinical aspects. The purely mathematical and mechanical studies were excluded. We used a qualitative-interpretive approach for data extraction by reading through the selected articles and taking notes in an excel file.

2. Results

According to our search strategy and selection method, 12 papers for the structural model and 7 papers for Fluid-Structure Interaction (FSI) of the aortic valve were selected.

Computational fluid dynamic (CFD) is used to simulate and study body structures, systems and their common phenomena based on numerical and mathematical methods. Compared to other fields, CFD is emerging in medicine [10,11]. The progress in the modern computers’ power and algorithms have caused a significant decline in the processing time and cost and consequently facilitated CFD based medical studies [11]. Also the advanced tools for taking the 3-D high-resolution medical image and image processing algorithm have increased the model accuracy and led the idealized model to patient specific ones and Image based Computational Fluid Dynamic (iCDF) [9]. Progress in clinical simulation is to the extent that the results are statistically analyzed and used in clinical decision support systems (CDSS) [9]. Also a virtual experimental platform that can be provided by these models is usable in training systems for new vascular surgeons or anaesthesiologists [10].

In the last decades, the importance of the cardiovascular diseases caused the widespread growth in using CFD for pathology, better understanding of the cardiac and valves function, surveying the hemodynamic phenomena, designing and improving prostheses and interventions [10,11]. Two categories can be considered for the aortic simulations in the selected papers:

1. Dry models (Structural models neglecting the tissue and flow interaction)
   At first these kind of simulations concentrated on studying the prosthesis [12-16,19,22], their functions and various conditions like changing in pressure [1,13], stress [12], stent height [13], material properties [15,16,19], etc. Their results were used in designing bioprosthesis or mechanical prosthesis. With the developments in the medical imaging, simulations of natural valves have become common [17,18,20,21] and models have created based on the magnetic resonance imaging (MRI) [17,18], computed tomography (CT) [20] and even digital [21] images.

2. Fluid–Structure Interaction (FSI) models
   Considering the effects of the blood flow interaction with the valve and its function can make the model more realistic. These kind of aortic models were created to investigate the influences of the flow on the stress or strain [24] and valve function [25,26], better understanding of the valve’s mechanical behavior to make clinical decisions [27,28], study the effect of annulus diameter on the stress or strain [30] and etc.
The Finite Element Method (FEM) [12-19,23-27,30] and the Finite Volume Method (FVM) [30] are two common methods for developing dry models. These methods don’t consider the flow and tissue interaction and may affect the result’s accuracy. Although FSI has more complexity and higher computational cost it is more accurate as it considers this interaction [29]. Also unlike the dry models, FSI models are capable of considering physiological boundary conditions [27,29,30].

Because of the complexity of the valve mechanisms and tissues, some assumptions have been considered to simplify the models. For instance in some papers just diastolic phase [12,13,18,20,30], in some other just systolic phase [14,19,26,27] and in some both phases have been simulated [15,24,25,29]. For simplifying the models, not all the parts have been simulated. For example simulated parts included the valve [19,23], valve and root [18,20,21,24-26,30]. Another example of these assumptions have related to material’s properties of the aorta. Although they are non-linear, anisotropic and elastic [19,22], they have been considered linear [14-18,25,26,30] or isotropic [12-15,26,30] or rigid [12,13,15,24,30]. Besides, not too much attention was paid to the evaluation of the models but some models were compared to the clinical literatures and other simulated models [16,17,19,24,29,30].

3. Discussion

The present literature attempts to review the common methods of clinical simulations for the cardiovascular system and especially simulation of the aortic valve. This review revealed that among CFD methods, FEM and FVM were more common compared to other methods. Progress in this field has made it possible to create patient specific and image based models with considering flow and tissue interaction. Although the simulation results can be useful for designing CDSS, platform for training, informing physician etc., we didn’t find these applications in the selected papers. We just found a study that designed a CDSS based on simulation for endoprosthetical tracheal surgery [9].

This review didn’t consider the purely mathematical and mechanical papers and focused on identifying the necessary methods and properties for cardiovascular simulation. In order to create the models with maximum usability potential we recommend to develop an idealized model for thorough understanding first and then create the patient specific ones. Various methods were used for the evaluation of models like comparison with published experimental data or other simulations’ results but the best method is comparison with the patient’s measurements. According to clinical simulation’s potential, there is a need to pay more attention to its related aspects like design or optimization of the methods and analysis of the results.

References


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