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Procedia Materials Science 10 (2015) 706 – 713

Procedia Materials Science

www.elsevier.com/locate/procedia

2nd International Conference on Nanomaterials and Technologies (CNT 2014)

Simulation of pulsatile blood flow through various cardiac defects and quantitative measurements of shunted blood volume

Vaibhavi A. Sonetha[a,c], Jayesh R. Bellare[a,b,*]

[a]Centre for Research in Nanotechnology and Sciences, Indian Institute of Technology Bombay, Mumbai 76, India

[b]Department of Chemical Engineering, Indian Institute of Technology Bombay, Mumbai76, India[c]Department of Biomedical Engineering,D. J. Sanghvi C. O, E, Mumbai 56, India

Abstract

Congenital heart defects such as Atrial Septal Defect (ASD), Ventricular Septal Defect (VSD) and Patent Ductus Arteriosus (PDA), which are the most common ones, are treated with minimally invasive surgery using occlusion devices. Newer devices have been proposed on micro- and nano-materials. To improve efficiency and to reduce failure of this mode of treatment, it is important to simulate blood flow through defect before and after placement of device and calculate shunting of blood volume. We present here blood flow through atria and aorta in normal and defect conditions. Finite Element Analysis (FEA) is used for modeling and simulation using ANSYS 14.5. Blood is simulated as Newtonian and incompressible with pulsatile nature. The model of upper two chambers of heart is modeled with and without ASD. The simulation showed shunting from left atrium to right atrium in case of ASD and volume of shunted blood is calculated with variation in shape and size of defect. PDA is modeled as tube between pulmonary artery and aorta, and shunting is calculated with variation in shape and size of PDA. The simulation can be extended further by simulating placement of device in defect and evaluating its efficiency in terms of occluding the defect. Our simulation could enable novel designs based on nano-materials and treatment modalities.

Peer-review under responsibility of the International Conference on Nanomaterials and Technologies (CNT 2014)

Keywords: Occlusion device, pulsatile blood flow, ASD, PDA

1. Introduction

Congenital heart defects (CHD) which are present from birth are defects in structure of heart. The most common CHDs are Atrial Septal Defect (ASD), Ventricular Septal Defect (VSD) and Patent Ductus Arteriosus (PDA). A defect between heart's two upper chambers called atria is known as atrial septal defect and a defect between heart's two lower chambers called ventricles is known as ventricular septal defect. A duct connecting aorta and pulmonary

* Corresponding author. Tel.: + 91 22 25767207; fax: + 91 22 25726895, +91 22 25723480.
E-mail address: jb@iitb.ac.in

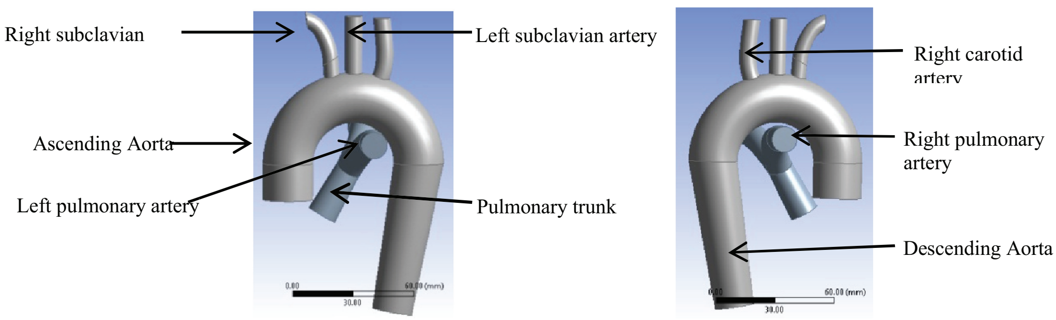
artery is known as patent ductus arteriosus. These defects can be treated with medications in few cases but many of them require surgery. Minimally invasive surgery is preferred over open heart surgery due to reduction in postoperative recovery time, pain, discomfort, long hospital stay, residual surgical scar, psychological trauma and most importantly risk involved in open heart surgery. In minimally invasive surgery, Intravascular Prosthetic Devices known as occlusion devices are placed inside blood vessels to regain original or desired flow conditions. Occlusion device is implanted inside the human body using catheterization. It acts as physical barrier to the flow facilitating thrombogenesis and eventually occludes the abnormal connection. Complications such as erosion of tissue, displacement and breakage of device, sudden death are serious concerns with this mode of treatment. This suggests simulation and mechanical evaluation of device under patient specific biological condition prior implementation which can be performed using Finite Element Method (FEM) and computational fluid dynamics (CFD). Similar simulations were conducted on stents by Hsiao et al. (2012) and on flow diverters by Ma et al. (2012). Aortic flow was simulated by Jeong et al. (2011). Flow through ASD and PDA were simulated but with constant blood pressure by Sonetha and Bellare (2014). We present modelling and simulation of pulsatile nature of blood flow through vessels and chambers of heart under normal condition and defect condition such as ASD and PDA. The shunting of blood is calculated from different sizes and shapes of defect.

2. Method

Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD) are the techniques used for simulation of blood flow through heart using ANSYS 14.5. The vessels and chambers of heart are modelled with and without defect. Blood is simulated as Newtonian and incompressible with blood density 1060 Kg/m^3 and dynamic viscosity 0.005 PaS. Blood pressure has pulsatile nature and it varies between 80 to 120 mmHg i.e. 10666 to 16000 Pa. To model flow through the heart, the pulsatile nature of blood flow is considered.

2.1. Model of vessels and chambers of heart

The aorta and pulmonary are modelled as shown in figure 1 with dimensions as in table 1. PDA is modelled as abnormal connection between aorta and pulmonary artery as shown in figure 2. Three different shapes such as cylindrical, concave and convex with two different sizes of diameter such as 3 mm and 6 mm are considered for PDA.



(a) (b)

Fig. 3.1 Aorta and Pulmonary artery (a) Front view; (b) Back view.

Table 1. Dimensions of aorta and pulmonary artery

Vessel	Diameter	Boundary condition
Ascending aorta	20 mm	Velocity inlet
Right and Left subclavian artery	8.8 mm	Pressure outlet
Left carotid artery	8.8 mm	Pressure outlet