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Original article

Evaluation of a novel extra-cardiac Fontan procedure with implantation of a biocompatible membrane

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Abstract

Fontan operation is a final palliative surgical treatment for patients with a single ventricle (SV) physiology. One of the common disadvantages of Fontan operation is to generate a non-pulsatile flow instead of the normal pulsatile flow produced by contraction of the ventricle. Theoretically, in SV patients, maintaining the antegrade flow through pulmonary valve can produce flow pulsatility in the right and left pulmonary arteries. However, it not only increases the energy loss in the Fontan of total cavopulmonary pathway (TCPC), but also imposes an extra load on pulmonary arteries as well as the ventricle.

In this study, the potential capability of pulmonary valve of the patient that can be used to increase the pulsatility of blood flow in pulmonary arteries, as a novel concept, is introduced and evaluated by using numerical simulation. In this approach, the main pulmonary artery of the patient is repaired and a flexible membrane is constructed by sewing the leaflets of pulmonary valve (three cups) together, through Fontan surgery. This membrane would fluctuate by high gradient pressure that is imposed from univentricular heart in each cardiac cycle. Alternatively, more dilatable materials, as flexible artificial membranes, are also considered to examine the effect of membrane's compliance on blood flow in pulmonary arteries. In this work, we have used the flow solid interaction (FSI) simulation to investigate the effect of mechanical properties of the membrane material on the pulsatility of velocity profiles.

1. Introduction

There are many congenital heart diseases with single ventricle physiology. In all these, the single functional ventricle should work as the ventricle supporting the systemic circulation and the other missing ventricle should be bypassed by using any variant of Fontan operation.

Ventricular volume overload and arterial desaturation are two main adverse consequences of a single ventricle physiology. Various surgical palliations have been developed and tailored by the precise anatomy of the cardiac lesion in each individual patient. In some cases, a modified Ballock–Tausiing shunt is established in the first 6 months of life, which is taken down later. Then a bidirectional Glenn shunt is performed and finally total cava blood flow is diverted into the pulmonary arteries through total cavopulmonary connection (TCPC) of Fontan operation. Many of these patients have a pre-existing pulmonary stenosis or have undergone a previous pulmonary arterial banding for avoiding development of pulmonary arterial hypertension. Fontan operation, as a terminal palliative measure improves the quality of life in postoperative patients susceptible to numerous long-term complications [1–3].

Clinical studies demonstrated that the structure of TCPC has a crucial role in the loss and consequently Fontan outcomes. Besides, high shear stress on the vessel walls can cause thrombus formation. Some clinical studies such as KrishnankuttyRema et al. [4] and Fogel et al. [5] investigated the distinction of hemodynamics in different TCPC anatomies. Hjortdal et al. [6]

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Abbreviation

TCPC	Total cavopulmonary connection	PS	pulmonary stenosis
RPA	Right Pulmonary Artery	PI	Pulsatility Index
LPA	Left Pulmonary Artery	PF	Pulsatile Flow
IVC	Inferior Vena-Cava	MRI	Magnetic Resonance Imaging
SVC	Superior Vena-Cava	FSI	Fluid Structure Interaction
PA	Pulmonary Artery		

quantified TCPC flow rates during rest and exercise conditions using the real-time PC MRI and demonstrated a compromise between the pressure drop and flow distribution in TCPC.

In addition, progress in Computational Fluid Dynamic (CFD) enables the researchers to perform numerous simulations. It has reported that geometrical characteristics of TCPC can greatly influence the outcome of the surgery. For instance, if the TCPC geometry imposes a high pressure drop or high wall shear stress, the patient will encounter with the danger of low oxygen saturation or thrombus formation, especially under exercise condition. Thus patient-based simulations could be extremely valuable in decision about the optimized TCPC geometry for the Fontan surgery. Marsden et al. [7] and Yang et al. [8] showed that adding a Y-graft modification reduces the energy loss significantly and results in more equal distribution of IVC flow between the left and right lungs compared with traditional T-shaped TCPC geometry.

Another side effect of the Fontan is the non-pulsatile pulmonary blood flow; since the right ventricle being bypassed. Although Throckmorton et al. [9] employed a pump to facilitate the blood flow in circulatory system, because of using implanted pump device it increases the risk of thrombus formation. Moreover, it needs an external power supply and reduces the patient comfort. Hence, using the natural capacity of patients for making pulsatility of the blood flow without employing other external device is an interesting research.

There is another way for increasing the pulsation of blood flow in Fontan surgery. It offers to maintain a little blood stream through main pulmonary artery, which is called restrictive antegrade pulsatile flow. Since in most single ventricle patients, there is a high blood pressure behind the pulmonary valve, it could make a pulsatile flow through pulmonary stenosis and increase the pulsatility of pulmonary blood flow. Several studies are advocated the potential benefit of leaving pulsatile sources of antegrade pulmonary blood flow after bidirectional cavopulmonary anastomosis (BCPA) procedure [10–12]. Wal et al. [13] represented that the mean pulmonary artery pressure and oxygen saturation with accessory pulsatile flow were significantly higher and no pulmonary hypertension developed. They showed that long-term survival following Fontan with accessory pulsatile flow is significantly better than conventional Fontan and associated with better pulmonary artery growth. However, Fontan patients are still susceptible to numerous, long-term complications. Monjezi et al. [14] demonstrated that using stenosed PA (pulmonary artery) is significantly effectual in increasing intensity of flow pulsation but it also increases the energy loss in TCPC and imposes an extra load on the heart. As a result, the permanent increase of the heart power might threaten the long-term efficiency of the operation. For example, it could cause an increase in the volume of the heart and cause hypertrophy. Also, increasing the pulmonary-to-systemic flow ratio can result in inadequate systemic oxygen delivery and mortality after the surgery. One of these complications is that the liver encounter to a great risk of hepatic fibrosis due to no pulsation.

To overcome this shortcoming, we have presented the concept of implantation of a biocompatible membrane in stenosed PA branch. The advantage of this method is simply transmitting cardiac pulsations without (adding extra flux to the TCPC) overloading the heart. The first option was construction the membrane by using the patient's pulmonary artery. In this concept, three cusps of the patient pulmonary valve could be repaired and sewn in an operation. Consequently, the sewn membrane will act as a diaphragm and will oscillate because of different pressure exists between two sides of it means the ventricle and TCPC. Although the main objective of this new procedure is based on using repaired pulmonary valve of the same patient, an artificial biocompatible membrane is also assumed, in order to examine the effect of more dilatable membranes. We assume that these membranes could be prepared from Polytetrafluroethylene (PTFE) and Polyether or Polyurethanes which have been used widely as barrier membranes and vascular graft in several studies [15]. The effect of pulsation of these membranes on fluid domain is the major objective of this study and solid mechanics assessment of the membrane is not considered here.

In the present study, the effect of implanted membrane is evaluated using numerical simulation. In order to describe the membrane interaction with blood, Fluid Structure Interaction (FSI) simulation is used. So, we have investigated the effect of mechanical properties of the membrane on the flow pulsation.

2. Materials and methods

The geometry of T-shaped model is constructed based on MRI images, which have been taken from a 9-year old girl's thorax after a successful extra-cardiac Fontan surgery. We have used 3 anatomical slices with 6 mm thickness as Figs. 1a to 1c show. The model inlets and outlets have been extended virtually to provide the fully developed flow condition depicted in Fig. 1f. The length and diameter of PA are extracted from the anatomical data.

In this new approach, a bio-membrane will be implanted in the middle of main PA as shown in Fig. 1f. This first option