Computational haemodynamic analysis of patient-specific virtual operations for total cavopulmonary connection with dual superior venae cavae

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Abstract

OBJECTIVES: This study set out to design different types of total cavopulmonary connections (TCPC) with dual superior venae cavae (SVC), taking into account different sites for anastomosis from venae cavae to pulmonary arteries (PAs), and to compare haemodynamic features in these virtual operative designs.

METHODS: The geometries of bilateral bidirectional Glenn (BBDG) connection and inferior vena cava (IVC) connected extracardiac conduit were reconstructed to three-dimensional configurations according to the magnetic resonance images (MRIs) of two patients at the same age, and virtual operations were designed to create four possible TCPC models under the guidance of paediatric cardiac surgeons. Computational fluid dynamic (CFD) simulations were performed in each model at five predetermined pulmonary flow splits, to predict postoperative blood flows. The same boundary conditions were applied on each model, in order to simplify the analysis of the influence of configurations on the flow characteristics. Control volume power losses and energy efficiency in different models were calculated and compared. Flow patterns in the models were demonstrated by streamlines corresponding to the venae cavae.

RESULTS: When the flow rate of the right pulmonary artery (RPA) was 40–60% of the total pulmonary flow, control volume power loss was lower than the other three models in the model of TCPC 2 and was higher than the other three models in the model of TCPC 4.

CONCLUSIONS: For this patient, anastomosing the left superior vena cava (LSVC) and right superior vena cava (RSVC) on the PAs close together will cause higher power loss and lower energy efficiency in the TCPC connection. If the LSVC and RSVC had been connected to the PAs as near as possible to stimulate growth of the central PAs when performing I-stage BBDG procedure, the extracardiac conduit from IVC would be better connected just under the anastomotic site in the following TCPC procedure to avoid high power loss.

Keywords: Virtual operation · Computational fluid dynamics · Total cavopulmonary connection · Bilateral bidirectional Glenn procedure · Haemodynamics

INTRODUCTION

Total cavopulmonary connections (TCPC) procedures are performed on children with congenital heart diseases resulting in only one functional ventricle, such as tricuspid valve atresia, mitral valve atresia and hypoplastic left heart syndrome [1–3]. At the completion of TCPC procedure, both the superior vena cava (SVC) and inferior vena cava (IVC) are connected to the pulmonary arteries (PAs) bypassing the right part of the heart. Although short-term survival rate has been greatly improved by the development of surgical techniques and postoperative care, the long-term survival rate and postoperative quality of life have not been improved significantly [4–6]. Among the variables leading to poor clinical outcomes, energy efficiency of the connection was considered to be a key factor which could be controlled by appropriate operative design [7].

The difference in haemodynamics between primary conditions and TCPC is so marked that many patients cannot safely undergo I-stage TCPC operation. Bidirectional Glenn (BDG) procedure is used as a standard interim procedure before the final TCPC operation [8, 9]. By end-to-side anastomosis of the SVC to the PA, blood returning from the SVC flows into the left pulmonary artery (LPA) and right pulmonary artery (RPA) simultaneously, which allows stepwise adaptation of the ventricle geometry to the change of volume load in the interval between primary conditions and final TCPC procedure.

During embryological development of systemic veins, failure of obliteration of the left anterior cardinal vein results in the persistence of the left superior vena cava (LSVC). Persistent LSVC affects approximately 0.3% of the population. Its prevalence increases to...
2–4.5% in patients with other congenital heart defects [10]. To treat patients who were born with functional single ventricle and persistent LSVC, the bilateral BDG (BBDG) procedure is commonly applied, in which both LSVC and right superior vena cava (RSVC) are connected to the PAs. Although BBDG and the subsequent TCPC procedure are now widely used in the treatment of patients born with functional single ventricle and persistent LSVC, the appropriate distance between the sites for anastomosis of the LSVC and RSVC to the PAs, as well as the appropriate site for anastomosis of the IVC conduit to PAs, have remained controversial. Developments in medical imaging and the improvements in computational fluid dynamic (CFD) processing capacity have made it possible to simulate and analyse the complex flow features in cavopulmonary connections [11–14]. In this study, virtual TCPC procedures were performed to design four different TCPC configurations with dual SVC based on magnetic resonance imaging (MRI). The results of CFD simulations were analysed to investigate the control volume power losses as well as haemodynamic characteristics at the connection area of these models.

MATERIALS AND METHODS

Patient data

Two patients were retained for this study. Patient 1 was a 5-year-old boy who was born with congenital absence of the spleen, univentricular heart, transposition of the great arteries, complete common atroventricular canal, pulmonary stenosis and persistent LSVC. He had undergone BBDG procedure at the age of two. The azygos vein had been ligated in this procedure. Patient 2 was also a 5-year-old boy who was born with pulmonary atresia, transposition of the great arteries and complete common atroventricular canal. He had undergone Glenn procedure at the age of 18 months and then extracardiac conduit TCPC procedure at the age of four. Informed consents were obtained and all associated studies were approved by the ethics committee of Shanghai Children’s Medical Centre.

MRI was performed on each patient using a 1.5 Tesla Signa Hispeed scanner (General Electric Company, USA) and series of continuous cross-sectional 6 mm-thick Fiesta sequence MRIs was acquired for three-dimensional reconstruction of the anatomies. In addition, magnetic resonance phase contrast velocimetry was used to acquire the average volume flow rate in the vessels of Patient 1. Average flow rates of the LSVC, RSVC and IVC in Patient 1 were 0.82, 0.46 and 1.20 l/min, respectively.

Anatomical model reconstruction and virtual total cavopulmonary connections operation

The MRIs of the two patients were imported into Materialise® Mimics 12.0 for three-dimensional reconstruction of the patient-specific vascular configurations and also for the virtual TCPC operations on the basis of these configurations.

The process of virtual TCPC operations is illustrated in Fig. 1. According to the MRIs of Patient 1, the geometrical model of BBDG 1 and the IVC was reconstructed. Then the LSVC and RSVC in BBDG 1 were cut near their anastomotic sites on the PAs and exported as two separate configurations. By changing the spatial location of the LSVC and RSVC relative to the PAs, we made the anastomotic sites closer, under the guidance of an experienced paediatric cardiac surgeon, to generate BBDG 2. The geometry of the extracardiac conduit was reconstructed according to the MRIs of Patient 2 to serve as a component for virtual operation. We connected the IVC with BBDG 1 and BBDG 2 at the middle of the two SVC-PA anastomotic sites and at the RPA, respectively, using the same extracardiac conduit reconstructed from Patient 2, to perform virtual TCPC procedures, keeping the IVC of Patient 1 in its natural anatomical position. Then the five branch vessels were cut orthogonally to their axes near their distal ends for the subsequent haemodynamic analysis. In order to guarantee the comparability of different TCPC models as far as possible, the vessels were cut at the same position on each branch vessel. Finally, four geometrical models of TCPC (TCPC 1, -2, -3 and -4) were generated, as shown in Fig. 2.

Numerical simulation

Governing equations. The Navier-Stokes (N-S) equations [15] and continuity equation for fluid dynamics describe the most general movement of fluid medium in the CFD simulations for blood flow. These equations are defined below:

Navier-Stokes equation: (Equation 1)

\[ \rho U \cdot \nabla U = -\nabla P + \mu \nabla^2 U \]

Continuity equation for fluid dynamics: (Equation 2)

\[ \nabla \cdot U = 0. \]

Where \( U \) is velocity, \( P \) is pressure; \( \rho \) and \( \mu \) are density and viscosity of the fluid. The homogeneous and Newtonian characteristics
of fluid with constant density of $\rho = 1060 \text{ kg/m}^3$ and viscosity $\mu = 3.5 \times 10^{-3}\text{ Pa·s}$ were assumed in the present studies [16].

**Mesh generation.** TCPC models were imported into ANSYS®-ICEM 13.0 for grid generation. The five branch vessels were extruded over a sufficient distance for computational purposes [17]. Tetrahedral mesh was generated in the central connection area and five boundary-fitted prism layers were generated at the near-wall regions to improve the resolution of the relevant scales in fluid motion. To find the best mesh for CFD simulation, we performed grid-independent verification in the model of TCPC 2 at LPA/RPA flow ratio of 50:50 by increasing grid number step-by-step at the central connection area and control volume power loss was calculated as an indicator to estimate grid sensitivity. We found out that over 400 000 cells in the central connection area were sufficient for the accuracy of the CFD simulation. Due to the similar volumes of the four TCPC models and the same computational conditions at the boundaries of each model, all the CFD simulations were performed with the grid number of over 500 000 in the central connection area for these four TCPC models. The grids of the central connection area are shown in Fig. 2.

**Computational fluid dynamics calculations and analysis.** CFD calculations were performed on the finite volume solver package ANSYS®-CFX 13.0 to calculate the laminar flow inside the connection area. Convergence of the simulations was based on the residual mean square (RMS) and the residual target was set as $1 \times 10^{-5}$. The conservation target was set as 0.0001. We assumed that the vessel walls were rigid and impermeable, with no-slip boundary conditions [18].

The average mass flow rates of LSVC (0.01448667 kg/s), RSVC (0.00812667 kg/s) and IVC (0.0212 kg/s) were imposed on the four CFD models as inflow conditions. The static pressure at the outlet of the extruded RPA was set as 1330 Pa and CFD simulations at five different levels of pulmonary flow splits (LPA:RPA = 40:60, 45:55, 50:50, 55:45 and 60:40) were performed in each TCPC model by varying the mass flow rate of LPA. All of the CFD simulations were run under steady inflow conditions.

Power loss has been commonly considered to be one of the most important aspects in the evaluation of a TCPC configuration. Control volume power loss within central connection area was calculated as follows [19]:

$$ E_{\text{loss}} = \sum_{\text{inlet}} \left( P_i + \frac{1}{2} \rho V_i^2 \right) Q_i - \sum_{\text{outlet}} \left( P_o + \frac{1}{2} \rho V_o^2 \right) Q_o. $$

(Equation 3)

Where $P$, $V$ and $Q$ are the mean static pressure, velocity and volume flow rate on the cross sections where the five vessels were cut ($i = \text{LSVC, RSVC and IVC}; o = \text{LPA, RPA}$).

Energy efficiency was calculated as described by Marsden et al. [20]:

$$ E_{\text{effic}} = \frac{E_{\text{out}}}{E_{\text{in}}}. $$

(Equation 4)

The flow features in the four CFD models were demonstrated by streamlines corresponding to LSVC, RSVC and IVC at LPA: RPA flow ratio of 50:50.

**RESULTS**

**Control volume power loss and energy efficiency**

Control volume power losses and energy efficiency at different levels of pulmonary flow splits in the four TCPC models were calculated and are shown in Figs 3 and 4. The control volume power loss in TCPC 2 is lower than the other three models and the energy efficiency of it is the highest at any predetermined pulmonary flow splits. On the other hand, the value of control volume power loss in TCPC 4 is higher than the other three models.
models and the energy efficiency of it is the lowest. The results of TCPC 1 and TCPC 3 fell in between.

The curves of control volume power loss versus pulmonary flow split are nearly median zygomorphic in the models of TCPC 1 and TCPC 3. The value of control volume power loss reached its lowest level at the LPA: RPA flow ratio of 50:50 in both of the models, which were 5.02 mW in TCPC 1 and 6.61 mW in TCPC 3. However, in TCPC 2 and TCPC 4, the control volume power loss generally kept decreasing as the RPA flow ratio increased. The lowest power loss in all the predetermined pulmonary flow splits in the four models was 4.90 mW in TCPC 2, when the LPA/RPA flow ratio was 45:55, as shown in Fig. 3.

Streamlines and flow patterns

The streamlines in the four TCPC models at LPA:RPA flow ratio of 50:50 were demonstrated by streamlines corresponding to LSVC, R SVC and IVC in Fig. 5.

In TCPC 1 and TCPC 2, the streamlines from the LSVC or R SVC flowed toward the PA on the same side. Differently, the streamlines from the LSVC or R SVC flowed toward both sides in TCPC 3 and that from the R SVC flowed toward both sides in TCPC 4. The decrease of the distance between the anastomosis sites of the LSVC and R SVC and the PAs made the stream from the superior venae cavae easy to flow into the heterolateral PA but caused chaos near the anstomotic sites which may result in higher power loss in TCPC 3 and TCPC 4.

DISCUSSION

The BBDG and following TCPC procedures have been widely used to treat patients born with functional single ventricle and persistent LSVC. The appropriate anastomosis sites from LSVC, R SVC and IVC to the PAs are still controversial today. We designed different virtual TCPC operative designs based on the geometries of BBDG and extracardiac conduit and performed CFD simulations on them to compare the control volume power losses and energy efficiency between these models.

Results showed that control volume power loss in the model of TCPC 2 was lower than the other three models, and that in the model of TCPC 3 was higher than the other three models at any predetermined pulmonary flow splits in this study. For this patient, anastomosing the LSVC and R SVC closely and connecting the extracardiac conduit from the IVC at the RPA will cause higher power loss and lower energy efficiency. Anastomosing the conduit from the IVC to the RPA with a large distance between the LSVC and R SVC showed the lowest power loss and the highest energy efficiency.

Daine A. de Zélicourt and colleagues have studied control volume power loss in a TCPC connection with persistent LSVC and concluded that control volume power loss decreased by shifting the IVC from under the R SVC to the middles of the LSVC and R SVC [7]. The results of our studies for TCPC 1 and TCPC 2 seemed different from their findings. However, analysis of the flow features by streamlines showed us the truth. The conduit used in de Zélicourt’s study had no obvious curve and was just under the R SVC, which made the stream from the R SVC and the extracardiac conduit interact with each other and caused chaos near the root of the R SVC, as described in their paper. In this study, connecting the extracardiac conduit in the middle of the anastomotic sites in TCPC 1 made the stream from the extracardiac conduit reach the root of the LSVC, due to the large curvature of the conduit, and then caused chaos and power loss because of the interaction of the stream from the IVC and LSVC. However, when the conduit was connected to the right in TCPC 2, no obvious chaos was found near the root of the LSVC or R SVC because of the large curvature of the extracardiac conduit, as shown in Fig. 5. So the actual conclusion of these two studies was the same: that if the stream from the IVC directly collided with the stream from the LSVC or R SVC and caused chaos, it would lead to high power loss. The curve of the extracardiac conduit was inevitable during the TCPC procedure because the existence of the heart and the position of the IVC cannot be changed in the TCPC procedure, because it is fixed in a specific patient. So, in this study, we kept the IVC of Patient 1 in its
normal anatomical position when connecting it to the PA with a curving conduit. Shifting the extracardiac conduit without considering the actual position of the IVC was not realistic and would inevitably influence the accuracy of power loss analysis.

The results showed that connecting the extracardiac conduit to the RPA and maintaining a large distance between the LSVC and RSVC may be a good choice when performing II-stage extracardiac TCPC procedure for this patient. Amodeo and colleagues have proposed a new type of BBDG, named ‘the unfidical bilateral bidirectional cavopulmonary anastomosis’, in which the LSVC and RSVC were amalgamated under the aortic arch, creating a single, confluent bidirectional cavopulmonary anastomosis, in order to stimulate the growth of the central PAs after the BBDG procedure [21]. However, according to the results of this study, reduced distance between the anastomosis sites from the LSVC and RSVC to the PAs will lead to higher power loss in the II-stage TCPC. So we think that, for this patient, a greater distance between the LSVC and RSVC should be a better option when performing a TCPC procedure: that is to say, joining the LSVC and the RSVC in the I-stage BBDG might stimulate the growth of central PAs but would have the potential to cause lower energy efficiency in the final II-stage TCPC connection. Were the LSVC and RSVC to be connected to a single anastomosis to the PAs to stimulate growth of the central PAs when performing BBDG procedure, the extracardiac conduit from the IVC would better be connected just under the anastomosis site, instead of on the RPA in the subsequent TCPC procedure, to avoid higher power loss.

The pulmonary flow splits were predetermined in this study, aiming to reflect different levels of pulmonary resistances on the two sides. The LPA/RPA flow ratio changed from 40:60 to 60:40 in this study; this range was sufficient for clinical analysis because no prominent stenosis was found in the LPA or RPA. However, it would be better if the real left and right pulmonary resistances of the patient were included in the numerical model in our future work, to make the study more patient-specific. Fortunately, numerical simulations at different pulmonary splits will give us an overall view of the flow features within this kind of connections and help us to understand the relationship of pulmonary splits and control volume power loss within them.

The average flow rate of the IVC in Patient 1 was set as inflow boundary conditions and the IVC-connected extracardiac conduit was reconstructed according to the MRIs of Patient 2. Because the conduit is a kind of standardized medical product with fixed physical properties, it is acceptable to perform virtual TCPC operations as described in this study. Furthermore, the main objective of this study is to investigate the influence of anastomosis sites from venae cavae to PAs on the flow features in this kind of connection, so the same geometry of the extracardiac conduit in different TCPC model is adequate for the purpose of this study.

One of the limitations in this study is that steady inflow rates were imposed on the three inlets: LSVC, RSVC and IVC. Actually, the flow in them fluctuates due to the heartbeat and the cyclic change of intrathoracic pressure caused by respiratory movement. Steady inflow boundary conditions may reduce the flow complexity of the flow features and decrease the power losses calculated in all of the models [22]. Fortunately, the influence is the same on each model and the main purpose of this study is to investigate the influence of configuration on the flow features in this kind of connection, so, in order to simplify the numerical simulations and make analysis of the results easy, we decided to impose identical steady inflow conditions on these models.

Although there are limitations as mentioned above, this study is an attempt to perform virtual TCPC operations and investigate flow features in the configuration of TCPC with dual SVC. Preliminary results acquired in this study will help paediatric cardiac surgeons to understand flow features within this kind of connection in more detail. Future studies will be aimed at imposing time-dependent inflow boundary conditions on the models and taking into account patient-specific pulmonary resistance to acquire more accurate and patient-specific results.

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