Computational Study of Mechanical Support to the Failing Total Cavopulmonary Connection

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Abstract: The performance of an axial flow blood pump in an idealized total cavopulmonary connection (TCPC) model was intravascularly evaluated. This blood pump was inserted within a modified Fontan surgery using a reinforced Gore-Tex conduit, to be connected to the caval veins with the pulmonary arteries. Two different computational models were examined (i) the new geometric model without a pump and (ii) with the pump. Computational fluid dynamics analyses of these models were performed to assess the hydraulic performance under varying pump's operating conditions. Numerical simulations indicate that the pump generates a pressure distribution which could prove to be beneficial for the univentricular patient with failing Fontan circulation, allowing to provide a possible intervention, at least as bridge to heart transplantation or as end-stage pump implant.

1 INTRODUCTION

Patients with single ventricle anomaly, even though this term groups very different pathologies, must deal with the condition of having only one of the two ventricles of adequate functional size. Some of the anomalies described as single ventricle defects include tricuspid atresia, hypoplastic left heart syndrome, double inlet left ventricle and other cardiac defects. The incidence of this heart defect constitutes about 1-2 % of all congenital heart defects (Samanek et al., 1999). Whenever there is only one ventricle capable to pump blood efficiently, the circulation must be reconfigured to maximize the efficiency of this single ventricle without overloading it.

The total cavopulmonary connection (TCPC) (Giannico et al., 2006) represents one of the most successful clinical options to obtain a sufficient lung perfusion in single-ventricle patients. It consists of the direct connection of the venae cavae to the pulmonary arteries, avoiding the usual pathway of blood through the right heart and then to the lungs, on account of the dysfunctional ventricle. Even though the survival to 15-20 years after surgery is superior to 82% (Gersony, 2008), statistics are nevertheless indicating that the risk of long-term failure of TCPCs is remarkable, ultimately requiring transplantation (Cromme-Dijkhuis et al., 1993).

Actually, the absence of the subpulmonary ventricle in the Fontan patient induces an elevation of pressure in the systemic venous circulation. The central venous pressure (CVP) rises to a mean pressure of about 12 mmHg, or even more in the most unfavourable cases (it can reach as high as 20 mmHg).

Clearly, an unphysiologically high CVP is poorly tolerated with time by the patients. In particular, it has deleterious effects on the liver and the splanchnic circulation, possibly resulting in protein-losing enteropathy and plastic bronchitis (Feldt et al., 1996), in the worst cases. At the liver level, the elevated CVP may induce complex liver dysfunction; consequently, the release of angiogenesis factors is expected, favouring the occurrence of venovenous anastomosis, pulmonary venous fistulas, and aortopulmonary collateral anastomoses (APCA).

Considering that a single ventricle must work against both systemic and pulmonary compartments, the ventricle itself faces a significant increase in total systemic resistance. Hence, the systemic ventricle undergoes hypertrophy, with elevated end-diastolic pressure, which diminishes its diastolic

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performance (Cheung et al., 2000; Gewillig, 2005). Also as a consequence of the elevated vascular resistance, the ventricular preload is limited, which also impairs diastolic performance.

As de Leval (1998) pointed out, the condition of the Fontan patient is paradoxical, in that there is systemic venous hypertension and simultaneously pulmonary arterial hypotension.

Many attempts have been made to optimize the Fontan connection, in order to make energy losses as negligible as possible (e.g., Amodeo et al., 2002). This notwithstanding, the failure of the Fontan circulation is an occurrence that must always be considered, with an increasing probability as a function of the time elapsed since the operation (Khairy et al., 2008).

Owing to the chronic shortage of heart donors, in recent years the possibility of using mechanical assistance for failing TCPC, either as bridge to transplantation or destination therapy, has been addressed in several studies.

In order to prevent ventricle hypertrophy induced by elevated vascular resistance and limited ventricular preload, it is natural to consider leveraging on the VAD technology already available to design therapeutic solutions for the unloading of the only functional ventricle in the Fontan patient.

In this viewpoint, different connections and assist devices have been proposed. Lacour-Gayet (2009) and others suggested the inclusion of an axial pump model used for circulatory support in an extracardiac tube that connects caval veins to pulmonary arteries, avoiding backflow in the superior vena cava (SVC).

An assistance device positioned in the SVC was found to increase the pressure in the PAs (Santhanakrishnan et al., 2013).

A pump installed in the inferior vena cava (IVC) is in principle capable of generating a strong pressure decrease, upstream of the device itself, possibly causing a collapse of the venous vessel. For this reasons, this study considers the insertion of a miniaturized axial pump inside a reinforced GoreTex conduit which connects the caval veins district to the pulmonary arteries district, in a different fashion with respect to the classical Fontan (TCPC) surgery. This connection, together with properly set pump operating conditions, was thought to improve the balance of arterial and venous pressures, preventing also vessel collapse, thanks to the surgical geometry and the use of a GoreTex prosthesis.

The herein selected device is supposed to solve the principal obstacles for long-term implantation. Various studies showed how the Jarvik 2000 pump might be among the major candidate for destination therapy due to its biomechanical characteristics, particularly for its very low hemolysis rate (Gibber et al., 2010).

The goal of the collaboration between the Biomechanics and Rehabilitative Technologies Unit of the Technology and Health Dept. of ISS and the Bambino Gesù Children's Hospital (BGCH) is to create a permanent solution to the failing Fontan connection as both bridge to transplant and destination therapy, avoiding the necessity of a subsequent transplant for the patient. Then, we selected an assist device whose long-term in vivo performance is well documented by the literature, representing a good reference model for a realistic therapeutic intervention. In this paper we study by CFD the feasibility of a surgical approach based on both an innovative surgical connection and the use of an axial pump model similar to the child-size Jarvik 2000, as a permanent solution to sustain the failing Fontan circulation.

The final aim of the investigation thus was to investigate the fluid dynamics of TCPC innovative connection making use of the mechanical support, defining the axial pump's condition for safe performance (range of flow rates, pump speeds, pulmonary artery pressures) to be related to the clinical setting to provide indication for a safe procedure in mechanical support of failing TCPC.

2 METHODS

This study of circulatory support device in the Fontan circulation uses a model of TCPC circulation, designed with an innovative connection with respect to traditional Fontan, and a model of cardiac pump resembling a pump already on the market, widely used as a Ventricular Assist Device (VAD), the child-size Jarvik 2000. The latter has the essential characteristics (function, size and form compatible with the insertion in a cylindrical tube) that are required for our research, among those most widely used in Europe.

The assistance device was positioned between the two caval veins and the pulmonary arteries, as shown in Fig 1. A second ideal geometric model characterized by cylindrical ducts of intersection between the caval veins and pulmonary arteries with no pump was also created for CFD study of the connection without mechanical support, in order to evaluate pressure and flow fields characterizing the connection used, with and without the pump.

Thus, two 3D clinical Fontan compartment models were created, using the computer aided design (CAD) software SolidWorks (SolidWorks, Concord, MA, USA), to study the properties of the flow inside the proposed model:

- a first model with an axial pump, whose design was inspired by the child-size Jarvik 2000 pump,
- a second model without the pump, in order to have a basis for comparison.

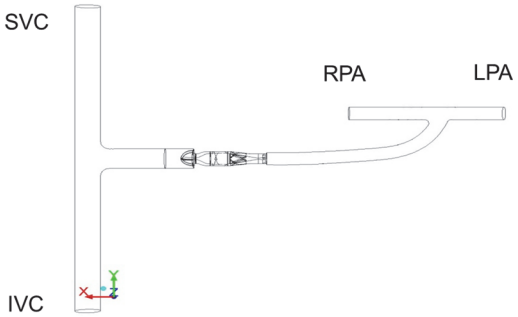

Figure 1: Model of the TCPC with assist device. At the left side the anastomosis between SVC and IVC is shown. At the upper right side the two pulmonary arteries are shown. A GoreTex conduit connects the caval veins and the PAs, with the axial pump inserted in the conduit.

In order to study the Fontan fluid dynamics, a vertically oriented tubular venous compartment of about 20-cm length was chosen to represent both IVC and SVC joined to the connected right-left pulmonary arteries by an extracardiac conduit. The pump model was positioned in the extracardiac conduit. The total volume of fluid in the model was approximately 83 cm^3, vs. the 2.1-cm^3 internal volume of the pump (priming volume), excluding the head input. The model was meshed using Gambit software, with almost 1,800,000 elementary volume elements, one million of which covered the 2.1-cm^3 internal volume of the pump.

Ansys Fluent 12.1 software was used for fluid dynamics simulations. To simulate the rotating part of the pump and analyze the behavior of the blood fluid during the stationary phase (when the pump is operating at full capacity), we used the RNG k-ε model, which has a better capability of studying rotating flows with respect to the standard k-ε model (Yakhot et al., 1992). This feature of the RNG k-ε model stems from more accurate transport equations for the turbulent kinetic energy (k) and rate of dissipation of turbulent kinetic energy (ε), with respect to the standard k-ε model.

The following performance conditions were imposed: pump angular velocities were within the child-size Jarvik 2000 range (4,000 - 18,000 revolutions per minute [rpm]) and 3 flow rate values (2, 3, 4 l/min) were considered. The pulmonary arterial mean pressures was set at 10 mmHg, and with a constant 40%-60% SVC–IVC flow ratio was considered, according to the physiological flow partition seen in children (Fogel et al., 1999).

Vessel walls were modelled as rigid tubes. A constant viscosity value of 0.0035 kg/m*s and fluid density of 1,060 kg/m3 were used (Cutnell and Johnson, 1998).

Animal Study – A preliminary investigation about feasibility of the presented approach in vivo was carried out on an animal model. All animals received humane care in compliance with the "Guide for Care and Use of Laboratory Animals". The Bambino Gesù Children's Hospital Ethical Committee approved all conditions for animal surgery and care.

A total of 8 sheep (Western breed, 42-48 Kg) were considered: 2 for preliminary studies, 4 supported and 2 non supported. Anesthetic drugs included ketamine (3 mg/kg), diazepam (0.2 mg/kg) and atropine (0.02 mg/Kg) and induction was obtained with propofol 1% (2mg/Kg). Animals were intubated and ventilated using a Servo 900C volume-cycled respirator (Siemens®, Danvers, MA) with 100% oxygen and 1% to 2% isoflurane. Ventilation parameters were: 10 to 15 breaths/min with tidal volumes of 10 ml to 15 mL/Kg and 4 cmH2O positive end expiratory pressure.

A 16 gauge femoral arterial line (Intracath®, Becton Dickinson, Sandy, UT) was placed for systemic blood pressure monitoring. A 16 gauge femoral venous line was inserted in a jugular vein.

The heart was exposed trough a median sternotomy. A fiber optic pulmonary catheter (Opticath®, Abbott Laboratories, North Chicago, IL) was placed in the main pulmonary artery. All pressures and flows were continuously monitored and recorded. CO, PVR, CI were calculated with Picco® (Pulsion Medical System) using thermo-dilution technique.

The SVC and IVC were sequentially divided from the right atrium and TCPC was performed by interposing a 16 mm polytetrafluoroethylene vascular graft (Gore-Tex®) between the two cavae and connected to the pulmonary artery through a second conduit in a T- junction geometry (2 non supported TCPC).

In the pump-supported group (4 animals), the child-size Jarvik 2000 axial pump was inserted in the conduit to the pulmonary artery. Flow rates were maintained between 2 to 3 L/m in a range of 5.000, 7.000 and 9.000 rpm, at 1st , 2nd and 3rd hour of support, respectively. The axial child flow pump was

positioned as distal as possible from venae cavae to avoid their collapse. The graft diameters were chosen to match the sheep's SVC and IVC dimensions. The main pulmonary trunk was left in place to vent the blood from coronary sinus. Hemodynamic variables were recorded over a period of 3 hours.

Hourly arterial blood gas measurements were obtained. In addition, oxygen saturations in PA and IVC blood, serum lactate levels were measured before and during operation.

3 RESULTS

Fig. 2 reports the pressure values obtained in the conduit, upstream of the device, at 1 cm downstream of the IVC-SVC anastomosis. Comparing the curves relative to the geometry with the pump with the line representing the connection without assistance, it can be seen that, for each imposed flow rate (2, 3 and 4 L/min), the pump does not constitute a resistance to the flow, at a sufficiently high angular velocity (e.g., from 10000 rpm upwards, for 3 l/min). Moreover, the pump can sustain flows of less than 2 l/min at speeds below 10000 rpm.

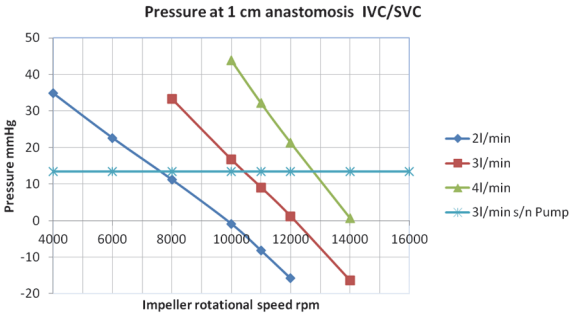

Figure 2: Average intravascular pressure, at 1 cm downstream of the IVC/SVC connection. The horizontal line indicates the value of the calculated pressure that would occur in the geometry without the pump, in the case of a flow rate of 3 l / min (similar values for other flow rates). Above the horizontal line the rotational speed is not usable for blood perfusion, whilst the pump represents an obstacle for the blood; thus the usable region for the pump speed in relation to the available venous pressure is comprised between the horizontal line and a pressure level close to zero.

These results are encouraging, since the axial pump is meant to be used in patients with low levels of physiological flow rate (children at the age of a few years).

The CFD study enabled also an assessment of the Wall Shear Stress (WSS) values on the surface of the different parts of the connection. As apparent from Figures 3 and 4, a positive correlation was found between regime conditions (pump angular velocity and blood flow rate) and magnitude of WSS.

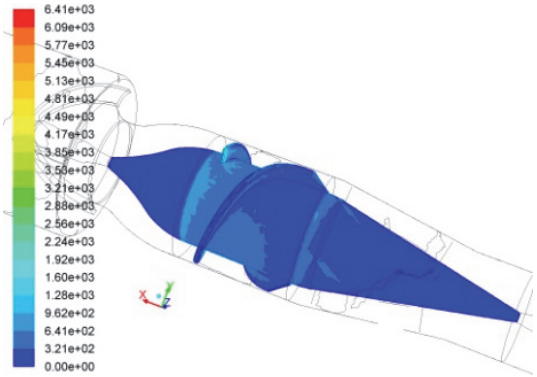

Figure 3: WSS [dyn/cm^2] distribution over the impeller's surface (pump angular velocity: 4000 rpm; blood flow rate: 1 l/min).

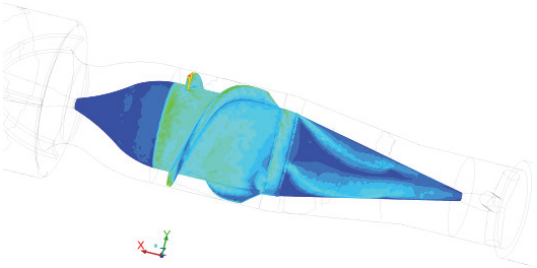

Figure 4: WSS [dyn/cm^2] distribution over the impeller's surface (pump angular velocity: 10000 rpm; blood flow rate:3 l/min). The color code is the same as in Fig. 3.

It must be underlined, though, that at the highest regime investigated the maximum WSS value was 6410 dy n/cm^2, which is not an excessively high value for shear stresses in physiological flows with prosthetic devices. As an example, in Grigioni et al. (2001) a value of around 5500 dyn/cm^2 was found for the maximum Reynolds shear stress associated to a bileaflet aortic valve available on the EU market.

Animal Study - The group without pump support had a sudden deterioration of hemodynamic parameters and they died within one hour. In the pump-supported (PS) group all animals survived and cardiopulmonary function was stable. No hemolysis at different run speeds, neither thrombotic events nor venous collapse was observed. In the PS group the central venous pressure values did not increase

during the mechanical assistance period, and were found to be similar to those in baseline condition.
As for the gas exchange values, arterial pH remained in the normal range, with slightly alkalosis after 3 hours, as an effect of moderate hypercapnia. A trend in lactates stability was observed under mechanical assist, which can be related to optimal hemodynamic function.

4 DISCUSSION

Heart pumps are available to assist the cardiac function in case of a pathological state. These devices are mostly implanted to assist ventricular function, hence they are called Ventricular Assist Devices (VAD). They aspirate blood from the ventricle and inject it into the aorta.

Apart from ventricle support, other uses of circulatory assistance have been proposed. The use of a pump for circulatory support proposed in this paper aims to solve the serious circulatory problems that quite often occur in patients previously operated on with Fontan surgery. The simulations herein presented show that it is possible to adapt an already available commercial VAD for extracardiac circulatory assistance. The original VAD connection has been modified to insert the device in the proposed connection. The CFD analysis allowed us to determine the range of rotational speed that should be imposed to avoid veins collapse. Fig. 2 can be used to gauge the upper limits of impeller rotational velocity, in order to prevent venous collapse. Considering an output pressure of 10 mmHg in the pulmonary arteries, the upper limits for 2 l/min, 3 l/min and 4 l/min are 10000, 12000 and 14000 rpm, respectively. When the flow is 2 l/min, Fig. 2 shows that at 10000-rpm rotational speed the pressure is -0.87 mmHg. This value is very close to the limit value of -0.5 mmHg reported by Riemer et al (2005) as a trigger for vein instability/collapse upstream of the pump. The problem in this case can be solved in two ways. The first one consists of reducing the rotational speed of the impeller; in the second, the length of the pipe connection can be increased, hence, at equal flow, a greater power loss will be obtained and the problem of excessive negative pressure can be minimized.

In the present study, we considered a constant rotational velocity of the pump. This was done for two main reasons: 1) the axial pump we referred to, the child-size Jarvik 2000, functions most of the time at constant angular velocity. Actually, the pump is restarted periodically, to mitigate the risk of stationary flow zones inside the pump, but the device is essentially a constant-speed pump. 2) Information about pulsatility in assist devices is still too scarce to implement a rational strategy of time-varying pump velocity for the failing Fontan. This notwithstanding, pulsatile assist devices in the future might be certainly an interesting option, taking also into account that pulsatility could reduce the risk of venous collapse, upstream of the device.

In order to minimize the possibility of venous collapse related to pump functionment, we tested the insertion of the device inside a reinforced tube (a GoreTex reinforced prosthesis). This solution avoids the collapse of the vein (very likely in extreme conditions) and prevents physiological or electronic random changes that could lead to a temporary low pressure with consequent collapse of the walls. The CFD simulations made on the model without the pump allowed us to calculate the pressures generated by the new connection, using the same boundary conditions for the model with the pump. To analyze the data provided by simulation with the pump inserted, we considered the pressure calculated in the model without the pump as the reference pressure, at a flow rate of 3 l/min (Fig. 2). A first comparison between the pathlines (data not shown) of the model without the pump and the one with the pump showed how the device provides an improvement in blood flow in the immediate vicinity of the anastomosis. The presence of the pump caused a reduction of recirculation region on the wall of the cava that is opposite to the junction between caval veins and conduit; this effect was due to the presence of a suction force generated by the pump which linearizes the flow. In the vessel downstream of the pump, spiral flow trajectories could be seen, caused by the torque generated by the impeller on blood flowing through the device. Before reaching the pulmonary arteries, the pathlines showed fairly linear trajectories, which demonstrate the effectiveness of the flow straighteners of the pump. Wall Shear Stresses are relevant if an end-stage implant is thought to be provided, thus WSS calculated values allowed us to verify that, predictably, the maximum values were correlated to pump speed and blood flow rate. In any case, the WSS values did not reach excessively high levels, confirming that the proposed study is a feasible approach to the treatment of the failing Fontan circulation as destination therapy.

The favourable role of the pump-assisted Fontan circulation, besides the results of the in-silico study, has been also confirmed by a preliminary animal study. Hence, we are confident that the growing

number of the Fontan patients with impaired function of the single ventricle will be offered in the future the possibility to avoid or defer as much as possible heart transplantation, by means of suitably designed mechanical assistance to circulation.

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