Artificial Organs

Presurgical Evaluation of Fontan Connection Options for Patients With Apicocaval Juxtaposition Using Computational Fluid Dynamics

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Abstract: Apicocaval juxtaposition (ACJ) is a rare congenital heart defect associated with single ventricle physiology where optimal positioning of the Fontan conduit for completion of total cavopulmonary connection (TCPC) is still controversial. In ACJ, the cardiac apex is ipsilateral with the inferior vena cava (IVC), risking kinking and collapse of the Fontan conduit at the apex of the heart. The purpose of this study is to evaluate two viable routes for Fontan conduit connection in patients with ACJ, using computational fluid dynamics. Internal energy loss evaluations were used to determine contribution of conduit curvature to the energy efficiency of each cavopulmonary anastomosis configuration. This percentage of energy loss contribution was found to be greater in the case of a curved extracardiac conduit connection (44%, 4.1 mW) traveling behind the ventricular apex, connecting the IVC to the left pulmonary artery, than the straighter lateral tunnel conduit (6%, 1.4 mW) installed through the ventricular apex. In contrast, net energy loss across the anastomosis was significantly lower with extracardiac TCPC (9.3 mW) in comparison with lateral tunnel TCPC (23.2 mW), highlighting that a curved Fontan conduit is favorable provided that it is traded off for a superior cavopulmonary connection efficiency. Therefore, a relatively longer and curved Fontan conduit has been demonstrated to be a suitable connection option independent of anatomical situations. **Key Words:** Apicocaval juxtaposition—Total cavopulmonary connection—Computational fluid dynamics—Presurgical planning—Fontan.

Since its introduction in 1971 (1), pediatric right heart bypass surgeries have evolved from atriopulmonary to extracardiac Fontan connections and also novel bifurcated inferior vena cava (IVC) connections (2–4) for improved hemodynamics targeted toward reduced systemic venous energy losses and optimal pulmonary flow splits in patients with complex univentricular physiologies. The two popular contemporary surgical templates for the final-stage palliative reconstruction surgical procedures are the intra-atrial lateral tunnel and extracardiac total cavopulmonary connection (TCPC) (5–7). From the standpoint of hemodynamics, previous computational and in vitro studies on several TCPC surgical templates with varying vascular anatomies (8) and patient-specific cardiac function (9) have revealed a range of hepatic flow distributions (10) and flow structures (11). However, a definite conclusion regarding the hemodynamic advantage of one surgical template type over the other is a clinical question that remains to be conclusively answered (12,13) due to this choice being dependent upon a host of variable patient-to-patient vascular factors.

A typical Fontan circulation involves connection of the systemic and pulmonary circulations in series. In such a connection, the postcapillary energy directs blood flow to the lungs and cardiac output is determined by transpulmonary flow (a function of pulmonary vascular resistance [PVR]) rather than the heart itself. A connection with minimal associated energy loss is therefore critical. Since its original description, the Fontan circuit has undergone several modifications in order to account for rare yet complex

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congenital heart defects with single ventricle physiology. Pediatric single ventricle heart disease with apicocaval juxtaposition (ACJ) is one such anomaly in which the optimal position of the Fontan conduit for completion of TCPC is still controversial. In ACJ, the cardiac apex is ipsilateral with the IVC, risking kinking and collapse of a conventionally oriented Fontan conduit, at the apex of the heart. Hence, the choice of route for the Fontan conduit requires keen examination by preoperative angiography or computed tomography and intraoperative findings play a vital role as well. The purpose of this study is to numerically evaluate different Fontan conduit connection options for patients with ACJ, using computational fluid dynamics (CFD) and presurgical planning (14).

Earlier studies have demonstrated that power losses are increased in TCPC templates due to insufficient caval offset achieved in the surgical reconstruction or sharp angles, resulting in less optimal clinical outcomes (15,16). Thus, the importance of streamlining the cavopulmonary connections for improving hydrodynamic design of the Fontan circulation is paramount. These factors, in addition to the patient-specific anatomical constraints, were considered in modeling in silico surgical options for Fontan connections evaluated in this study.

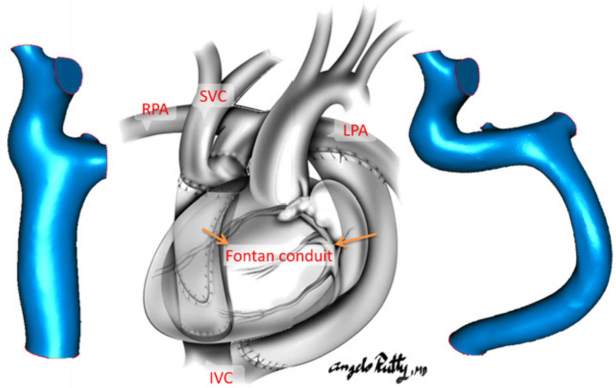


FIG. 1. Typical three-dimensional patient-specific presurgical options generated from MRI reconstructions, as per given surgeon sketches (middle) for LT-TCPC (left) and EC-TCPC (right). In both cases, the axis of the Fontan conduit was oriented toward the pulmonary trunk bifurcation. LPA, left pulmonary artery; RPA, right pulmonary artery; SVC, superior vena cava; IVC, inferior vena cava.

MATERIALS AND METHODS

Surgical procedures

The selected patient for this study initially had a Fontan surgery with atriopulmonary connection which had to be altered due to conditions of dilated atrium and atrial arrhythmia. Surgical Fontan conversion options are being evaluated in this study. In a Fontan circulation, as systemic venous energy powers blood flow to the lungs, a TCPC with minimal associated energy loss is therefore critical for improved likelihood of good surgical outcomes. Pathway selection in ACJ should be based on individual anatomy as well as hemodynamic function. The latter implies avoidance of pulmonary venous obstruction, and balancing of pulmonary flow (16). There are two variants to connect the transected IVC and the pulmonary artery in this scenario, that is, lateral tunnel (LT-TCPC) or extracardiac conduit (EC-TCPC). The former involves a shorter and straighter connection through the side of the ventricular apex ipsilateral to the IVC, whereas the latter involves the use of a curved and longer conduit traveling around the heart. The curved conduit travels behind the ventricular apex and is connected from the IVC to the left pulmonary artery (LPA), distal from the pulmonary artery bifurcation. Prior to surgery, the incremental benefit of one surgical option over the other was unknown and the patient was eventually operated on with the LT-TCPC option. Hence, we delineate a presurgical planning approach for this case that may also be employed to other patients in the future. The following sections of our manuscript examine the computational models of a representative case from each of the studied patient groups in an effort to distinguish between them from the standpoint of 3D internal hemodynamics.

Surgical planning by computational modeling

CFD is a powerful tool for simulation of internal hemodynamics in vascular conduits. For a quantitative investigation of the effects of different Fontan conduit pathways, an in-house anatomy editing tool is employed to create the virtual presurgical planning models, starting with a 3D surface model of the patient's superior vena cava (SVC), IVC, LPA, and right pulmonary artery (RPA) in their original anatomical orientations and positions. Patient-specific computational hemodynamic evaluations were conducted using such in silico surgical templates modeled from patient-specific presurgical magnetic resonance imaging (MRI)-reconstructed anatomies (see Fig. 1).

An in-house cardiovascular flow solver incorporating a validated 2nd-order accurate multigrid artificial compressibility numerical solver (17,18) was used to simulate incompressible and Newtonian blood flow with constant hemodynamic properties ($\rho = 1060$ kg/m^3, $\mu = 3.71 \times 10^{-3}$ Pa.s). Flow is simulated on a high-resolution unstructured Cartesian/immersed boundary grid with finite-difference numerical treatment. No turbulence model was applied in this study.

In silico models were developed for two connection options for a patient with ACJ, that is, LT-TCPC and EC-TCPC. As a case control evaluation serving as a baseline for making hemodynamic performance comparisons, an ideal LT-TCPC for the considered patient with a half diameter offset was postsurgically evaluated as well. This connection option was not feasible for the patient due to clinical complexities; however, it serves as a good ideal situation for comparison. All conduit connections were nonfenestrated. Steady caval inflow conditions were simulated under assumptions of incompressible flow and rigid, impermeable walls. Simulations were conducted at the resting phase contrast (PC)-MRI flow rates which are specified as fully developed Poiseuille flow velocity inflow boundary conditions, without extending the inlets. Forty percent of the mean ACJ patient cardiac output value of 3.9 Lpm is specified from the SVC. This is comparable to the standard cardiac output observed in Fontan patients (19,20). The IVC Reynolds number (Re) was 600, as per the presurgical MRI-computed flow splits and cardiac output of the patient, given the prosthetic Gore-Tex Fontan conduit selected for surgery was 24 mm in diameter. Outflow pressure boundary conditions are specified along with a set mass flow split, at the pulmonary arteries, as per observations from PC-MRI. The pulmonary mass flow distribution was 41:59 between the RPA and LPAs, respectively.

Furthermore, three independently evaluated "one inlet and one outlet" Fontan conduit models having different curvatures were also computationally modeled using CFD. These models were prepared as per surgeon sketches overlaid upon X-ray angiographic projections for three postsurgical TCPC patients. Two of these were LT-TCPCs having minimal curvature of the conduit, whereas one was a longer and more drastically curved EC-TCPC.

Unstructured Cartesian grids with ~300 000 nodes were considered for each of the above CFD evaluations, having a uniform grid spacing of 0.03 IVC inlet normalized length units (IVC diameter = 24 mm). The mesh density for the CFD simulation was deemed appropriate after a grid independence study conducted for the EC-TCPC model with a range of 100 000 to 300 000 nodes, in steps of ~50 000, using power loss across the anastomosis as the criterion for convergence in the running average flow field for steady caval inflow (Re 600 IVC flow).

Power loss analysis

Internal energy loss was evaluated across each Fontan conduit as well as across each of the modeled anastomosis. Evaluations were used to determine contribution of conduit curvature to the energy loss observed across the cavopulmonary connection. The power dissipated is calculated using a control volume approach proposed by Leefe and Gentle et al. (21). Neglecting thermal losses, the average power loss, E_{Loss}, at surface, dS, in the TCPC for one flow cycle with period, T, is calculated as follows:

$$E_{Loss} = -\frac{1}{T}\int_{o}^{T}\int_{CS}\left(p_{\text{static}} + \frac{1}{2}\rho u^2\right)u\hat{n}dSdt \qquad (1)$$

where p_{static} refers to the static pressure field and n is the normal to surface dS. The vector integrand of Eq. 1 prior to multiplication with the unit surface normal has been termed as the *energy vector*, ε. The difference between E_{Loss} computed at two or more surfaces enclosing a closed control volume is considered as a metric defining energy loss due to dissipative fluid interactions within that control volume. This metric was also used to characterize the different Fontan conduits (one inlet, one outlet) having different curvatures evaluated in this study, as well as to evaluate the energy loss across the whole cavopulmonary anastomosis by considering the difference in E_{Loss} between the two inlet and two outlet surfaces.

For steady flows, the running average product of total pressure and normal velocity at specific inlet and outlet surfaces chosen in the simulated anatomical model is considered in the E_{loss} computation. Static pressure was computed using CFD pressure drop values computed at each node in the model, relative to the IVC pressure.

RESULTS AND DISCUSSION

Computational evaluation—flow structures and power loss

Surgically constructed anastomoses result in energy dissipation, flow disturbances, and uneven distribution of pulmonary blood flow (16). These effects are magnified for higher flow rates which limit the exercise tolerance in patients after the Fontan procedure. Therefore, for purposes of making appropriate comparisons in this study, steady Re 600 IVC flow was modeled for the LT-TCPC and EC-TCPC models (see Table 1) as well as each of the independently evaluated one inlet and one outlet curved Fontan conduit models (see Fig. 2), as per mean

TABLE 1. *Energy loss analysis for the two modeled in silico surgeries: LT-TCPC and EC-TCPC*

	E_{Loss} (mW)						
Surgery	SVC	RPA	LPA	IVC anastomosis	IVC entrance	Net E_{Loss} (mW)	Fontan conduit contribution to net E_{Loss} (mW, % of net)
LT-TCPC	173.1	166.8	256.4	271.9	273.3	23.2	1.4 mW, 6.03%
EC-TCPC	177.1	177.0	260.1	265.2	269.3	9.3	4.1 mW, 44.09%

cardiac output and caval flow splits observed from the analyzed patient population.

Figure 3 compares the flow streamlines in LT-TCPC and EC-TCPC. It is clear that the straighter connection without a caval offset led to impingement or collision of SVC flow onto IVC flow. This increases the likelihood for stagnation of blood flow in the TCPC due to the extent of energy loss experienced on collision.

The extent of energy loss due to flow impingement was examined visually by coloring the flow streamlines with the magnitude of the energy vector, ε, in Fig. 4. Here, the change in initial inlet energy (blue) of the IVC flow is examined. The IVC flow has a markedly lower energy on collision in the LT-TCPC (yellow-red) in comparison with the EC-TCPC which showed higher energy at the flow confluence due to the presence of the swirling vortex propelling flow into the outlets. Figure 5 indicates that the swirling flow is certainly associated with greater vorticity as well. The SVC flow streamlines colored by vorticity highlight that the flow streams that were left unscathed by the presence of the collision region in the LT-TCPC had a relatively greater vorticity, whereas the streamlines in the collision region had low vorticity. This is telling regarding the fact that what is observed as flow impingement of SVC and IVC streamlines is actually not a recirculation zone but indeed a potential stagnation region. Stagnation regions present increased risk of thrombus formation and calls for an immediate surgical correction. In comparison, no such obvious collision flow or internal stagnation flow regions are observed in the EC-TCPC case due to the caval offset. Instead, the observation of coherent swirling vortical structures and helical outflow patterns seen at the LPA and RPA of the EC-TCPC case was found to be concordant with improved outflow hemodynamics and decreased energy loss at the flow confluence region. At the pulmonary branches, swirling flow is observed

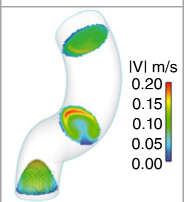
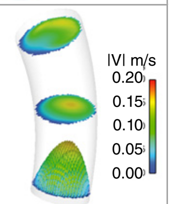
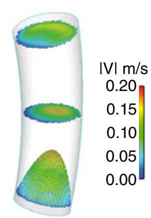
Independently Evaluated Fontan conduits				
Model	**E_{Loss} (mW)**		**Fontan conduit contribution (*mW*)**	**Figure**
	$ICV_{entrance}$	**$ICV_{minimum\ energy}$**		
Curved #1	99.86	96.67	3.190 mW	
Straight #1	91.41	88.83	2.576 mW	
Straight #2	56.45	54.69	1.759 mW	

FIG. 2. Comparison between percentage contributions to cavopulmonary energy loss by three different curved Fontan conduits (one inlet, one outlet). Results are contrasted against patient-specific presurgical plan case.

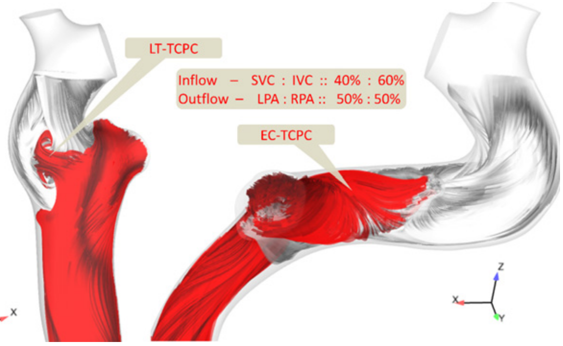


FIG. 3. Comparison between flow streamlines in LT-TCPC and EC-TCPC. SVC streamlines are marked in gray and IVC streamlines are marked in red.

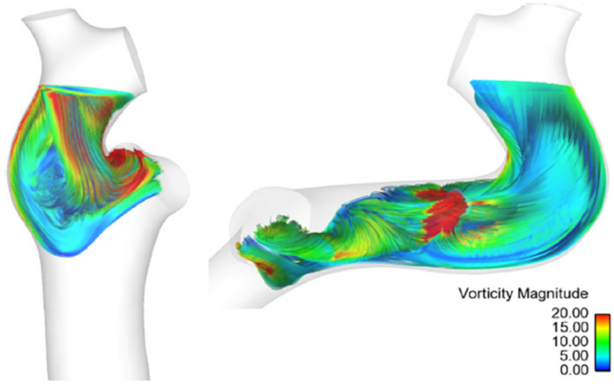


FIG. 5. Comparison between SVC flow streamline patterns as a result of IVC flow impingement, for EC-TCPC and LT-TCPC. Streamlines have been colored by vorticity magnitude. Regions of higher energy loss due to collision flow had low vorticity, whereas strong vorticity with a helical outflow pattern was characteristic of flow with minimized energy losses associated with collision.

in the ideal LT-TCPC configuration as well (seen in Fig. 4, bottom right). This effect is promoted by the caval offset and reduced energy is limited to the shear layer between the caval flows. One can argue that if it were possible to implement this connection option (which was not considered in the modeled ACJ complication), the 0.5-diameter IVC offset would have been ideal for the patient.

CFD results have indicated that contribution of internal energy loss within the Fontan conduit as a percentage of the total energy loss across the entire TCPC was greater in the case of the curved conduit (44%, 4.1 mW) than in the case of the straighter conduit (6%, 1.4 mW). In contrast, in the compared in silico connection models, the overall TCPC internal energy loss was significantly lower in the case of the EC-TCPC (9.3 mW) in comparison with the LT-TCPC (23.2 mW). This highlights that the trade-off for a curved Fontan conduit involving higher inherent energy loss may be a favorable option provided that the superior cavopulmonary connection efficiency is achieved. In this specific case, the ideal LT-TCPC had a net internal energy loss (8.4 mW) lower than both the proposed ACJ surgery options. This value is similar to internal energy loss values computed for typical completion lateral tunnel Fontan procedures by Bove et al. (16). In summary, the EC-TCPC was markedly better than the LT-TCPC connection and the higher internal energy loss inherent of the longer curved conduit was a favorable compromise when compared with an ideal connection option.

The independent Fontan conduit simulations have highlighted that the absolute values of internal

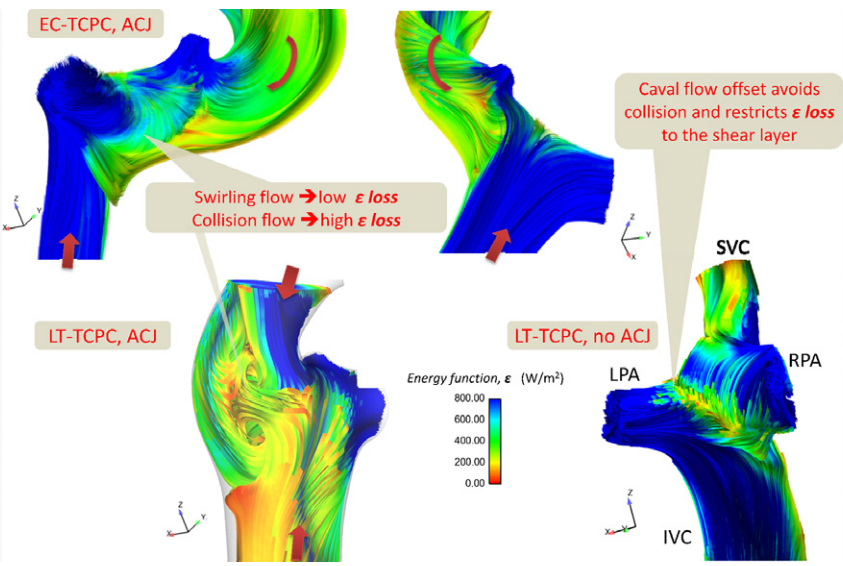


FIG. 4. Comparison between flow patterns in the EC-TCPC (top) and LT-TCPC (bottom). Major flow structures in the ACJ TCPC models were flow swirl structures created by SVC flow leaving at the LPA and RPA (seen in EC-TCPC case) and deformation in caval flow streamlines due to collision of IVC and SVC flow (seen in LT-TCPC case). Streamlines have been plotted from Fontan conduit flow depicting flow split. Colors of the streamlines correspond to the magnitude of the energy function. Swirling flow structures similar to the EC-TCPC were seen in for RPA outflow (right) in the control case, that is, ideal LT-TCPC. Notice that the energy function is lowest (indicating maximum dissipating) at the shear layer between the caval flows; however, the caval offset of the control case limited collision and overall energy loss.

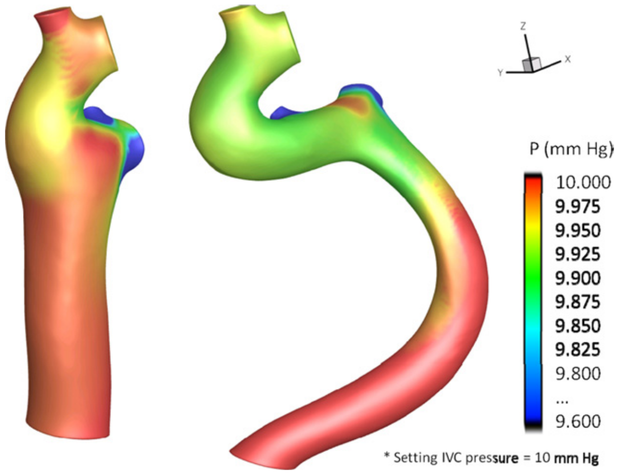


FIG. 6. Pressure distribution on caval conduits, scaled by minimum and maximum pressure noted in IVC. IVC inlet pressure was considered as 10 mm Hg in order to represent pressure values for this plot. Note that reference IVC pressure for CFD is a constant. Fontan patient-specific IVC pressures are typically higher than the normal central venous pressure range (2–6 mm Hg).

energy loss across the conduits are a useful index for characterizing them. The more convoluted the conduit, the higher is the maximum energy loss within it as the pressure drop across it will also be higher. In comparison, the straighter LT-TCPC conduits had smaller pressure drops across their ends as they were monotonically curved (Fig. 6).

As a final analysis of the effect of conduit curvature, the pressure field in the LT-TCPC and EC-TCPC cases was compared. Neither case had a pressure gradient across the TCPC in excess of 1 mm Hg between the IVC and central PA. This is consistent with the in vivo observations by Sakurai et al. (22). The pressure drop across the curved conduit was however notably higher than that seen across the straight conduit. Furthermore, a distinctly higher pressure region is seen in the curved inlet portion of the EC-TCPC conduit than the straighter LT-TCPC conduit. The higher pressure is indicative of slower flow and therefore the energy loss that is apparently occurring within the conduit to slow down the IVC flow. The more convoluted the path, the greater likelihood of flow stagnation and therefore thrombus formation. Therefore, the conduit curvature must be judiciously chosen in order to avoid a great extent of internal energy loss within it.

Energy loss in comparison with other hemodynamic factors

In a Fontan circulation, the systemic and pulmonary circulations are in series such that the systemic venous energy powers blood flow to the lungs. There is no doubt that improved cardiac output caused by decreased outflow resistance is desirable. In fact, single ventricle heart disease patient cardiac output is highly sensitive to the PVR (23). However, hemodynamic influence of the TCPC resistance to pulmonary flow has been shown to be comparable in magnitude to the PVR (typical values may be found in references [24] and [25]). Anastomosis configuration energy efficiency is important because the TCPC design goal is to dissipate away as little of that systemic venous postcapillary energy as possible so as to power flow to the lungs optimally. As simulations were performed at a constant cardiac output with constant mass flow split boundary conditions, the contribution of the anastomosis configuration to systemic venous energy losses is highlighted.

Our results indicate that the Fontan conduit must be offset from the SVC in a manner that averts a collision of flow streams and promotes swirling helical outflow at the proximal pulmonary outlets. The caval flow offset in the EC-TCPC case modeled in this study was approximately 1.5 IVC diameters. Clinically, in order to balance the IVC flow distribution between the RPA and LPA, the exact caval offset, that is, the position of the IVC anastomosis should be determined based upon pulmonary artery diameter and resistance determined based upon cardiac catheterization evaluation prior to surgery.

CFD versus actual patient outcomes

Reports by Sakurai et al. (22) have indicated no statistical differences in postsurgical hemodynamics between the LT-TCPC and EC-TCPC patient groups during the intermediate term, with respect to IVC pressure, left ventricular end-diastolic pressure, as well as cardiac index, therefore suggesting that the superiority of a single universally applicable optimal Fontan conduit route is not possible to arrive at independent of the patient-specific anatomical and physiological considerations using statistical analysis alone. A different optimal route needs to be determined for each patient. Our patient-specific study suggests that CFD is a promising patient-specific computational tool for noninvasive evaluation of surgical connection options which has the potential to inform the surgeon's choice of Fontan conduit routes for ACJ patients, based on quantitative and qualitative hemodynamic evaluation.

CONCLUSION

The Fontan operation is an imperfect solution for a complex cardiovascular problem. Preoperative evaluation is paramount for making the best decision regarding the most efficient Fontan connection. The interesting finding from this CFD study was that the detrimental influence that a longer curved Fontan conduit has on systemic venous energy loss was less than the effect of energy loss due to SVC and IVC collision flow in non-offset configuration. The curved Fontan conduit involving higher inherent energy loss has in fact proven to be a favorable compromise due to the greater connection efficiencies possible using EC-TCPC. Furthermore, it is difficult to construct the LT-TCPC in ACJ, whereas in comparison, the EC-TCPC is independent of anatomical situations. Hence, given the superior CFD determined efficiency of cavopulmonary connection possible by EC-TCPC, it presents itself as a viable option for patients, given that conduit size is appropriately selected as per the patient demographic classified by IVC flow. However, actual clinical choices must be made after considering many more factors than just internal energy loss at the cavopulmonary anastomosis; these include and are not limited to cardiopulmonary bypass surgical procedure time, necessity of aortic cross-clamp, and possibility of pulmonary arteriovenous malformations. The findings presented in this paper are meant to serve as an important aid for making decisions regarding Fontan conduit routes because they suggest that a surgeon should not hesitate to use a longer curved conduit from the energy loss standpoint if a straight conduit is subject to risk of compression due to patient-specific situations, as seen in ACJ. EC-TCPC is a suitable connection option independent of anatomical situations and can facilitate connections of superior efficiency in ACJ cases. CFD-driven virtual surgery prediction tools that aid this surgical decision-making process, once clinically implemented, will help objectify decision making regarding the optimal configuration from the standpoint of hemodynamic performance and eliminate trial and error during complex cardiac surgeries.

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