Cardiology in the Young (2016), **26**, 116–126
doi:10.1017/S1047951114002765

Original Article

Haemodynamic impact of stent implantation for lateral tunnel Fontan stenosis: a patient-specific computational assessment

Elaine Tang,[1] Doff B. McElhinney,[2] Maria Restrepo,[3] Anne M. Valente,[2] Ajit P. Yoganathan[3]

[1]*School of Chemical and Biomolecular Engineering, Georgia Institute of Technology, Atlanta, GA;* [2]*Department of Cardiology, Boston Children's Hospital, Harvard Medical School, Boston, MA;* [3]*The Wallace H. Coulter Department of Biomedical Engineering, Georgia Institute of Technology & Emory University, Atlanta, Georgia, United States of America*

Abstract *Background:* The physiological importance of the lateral tunnel stenosis in the Fontan pathway for children with single ventricle physiology can be difficult to determine. The impact of the stenosis and stent implantation on total cavopulmonary connection resistance has not been characteriszed, and there are no clear guidelines for intervention. *Methods and results:* A computational framework for haemodynamic assessment of stent implantation in patients with lateral tunnel stenosis was developed. Cardiac magnetic resonances images were reconstructed to obtain total cavopulmonary connection anatomies before stent implantation. Stents with 2-mm diameter increments were virtually implanted in each patient to understand the impact of stent diameter. Numerical simulations were performed in all geometries with patient-specific flow rates. Exercise conditions were simulated by doubling and tripling the lateral tunnel flow rate. The resulting total cavopulmonary connection vascular resistances were computed. A total of six patients (age: 14.4 ± 3.1 years) with lateral tunnel stenosis were included for preliminary analysis. The mean baseline resistance was 1.54 ± 1.08 WU·m^2 and dependent on the stenosis diameter. It was further exacerbated during exercise. It was observed that utilising a stent with a larger diameter lowered the resistance, but the resistance reduction diminished at larger diameters. *Conclusions:* Using a computational framework to assess the severity of lateral tunnel stenosis and the haemodynamic impact of stent implantation, it was observed that stenosis in the lateral tunnel pathway was associated with higher total cavopulmonary connection resistance than unobstructed pathways, which was exacerbated during exercise. Stent implantation could reduce the resistance, but the improvement was specific to the minimum diameter.

Keywords: Congenital heart disease; Fontan procedure; magnetic resonance imaging; computational modelling

Received: 13 July 2014; Accepted: 22 December 2014; First published online: 25 February 2015

THE LATERAL TUNNEL FONTAN PROCEDURE IS ONE of the main variations of total cavopulmonary connection for single ventricle physiology. The presence of native atrial tissue in the lateral tunnel pathway theoretically allows for growth of the pathway,[1] making this an attractive option for young children with complex congenital heart disease. One potential complication of a lateral tunnel connection is pathway stenosis, which may be associated with severe morbidity or subclinical dysfunction.[2–4] The geometry of lateral tunnel Fontan pathways is highly variable,[1,5,6] and even in patients without obvious stenosis the lateral tunnel pathway may be constructed with or develop relatively narrow segments of unclear physiological significance.

The placement of an intravascular stent is one method of treating lateral tunnel stenosis. In a recent study, Mets et al. reported stent implantation for lateral tunnel stenosis in 51 patients, effectively

Correspondence to: A. P. Yoganathan, Wallace H. Coulter Department of Biomedical Engineering, Georgia Institute of Technology & Emory University, Technology Enterprise Park, Suite 200, 387 Technology Circle, Atlanta, GA 30313-2412, United States of America. Tel: +1 404-894-2849; Fax: +1 404-385-1268; E-mail: ajit.yoganathan@bme.gatech.edu

increasing the pathway diameter and eliminating pressure gradients when present.[2] Many patients in that study, however, had angiographic narrowing without a pressure gradient at rest. Clinical measurement of pressure gradients in the venous non-pulsatile system is challenging due to limited sensitivity. For example, in a study of patients with severe extracardiac conduit Fontan stenosis by van Brakel et al,[7] catheterisation and angiography demonstrated mean pressure gradients of 2 mmHg at the most. Likewise, due to the variable and irregular anatomy and low pressures in the lateral tunnel pathway, the importance of an anatomic narrowing and the need for or benefit of stenting can be difficult to assess.[2] Therefore, the criteria for stenting patients with such pathway narrowing are empirical and the optimal diameter of the lateral tunnel stent may not be clear. In the report by Mets et al, stents were typically expanded to a diameter of 16–20 mm[2]; however, over-dilation of a stent may be of negligible benefit and has been reported to increase the risk of baffle disruption.[2]

The resistance created by a Fontan pathway stenosis can have a potentially substantial effect on the efficiency of a single ventricle circulation. We and others have previously demonstrated an inverse correlation between minimum Fontan pathway diameter and energy dissipation,[6,8] and have carried out computational studies that suggest a relationship between poor exercise tolerance and the non-linear increase in total cavopulmonary connection energy dissipation during exercise.[9,10] Fontan patients with extracardiac conduit narrowing improved their exercise tolerance after re-operation with a conduit of larger diameter.[7] Therefore, it is plausible that lateral tunnel stenosis, sometimes unrecognised, is one of the many factors that can adversely affect total cavopulmonary connection physiology, particularly during exercise.

In an effort to understand the haemodynamic impact of lateral tunnel pathway stenosis and its treatment by stent implantation, especially during exercise, and to explore how to better determine when stenting is indicated for lateral tunnel pathway narrowing, a framework for evaluating lateral tunnel stenosis and stent implantation using computational fluid dynamics simulations was developed. Numerical simulations were carried out under baseline and exercise flow conditions in patient-specific anatomies. The specific aims of this study were to demonstrate the use of a computational simulation tool to (1) evaluate the total cavopulmonary connection resistance with a stenotic lateral tunnel pathway, at rest and under simulated exercise conditions, before and after stent implantation, and to (2) investigate the effect of stent size on total cavopulmonary connection resistance to gain preliminary insight into possible intervention thresholds and targets.

Materials and methods

Patients

A subset of patients who underwent lateral tunnel Fontan palliation at Boston Children's Hospital and had post-Fontan cardiac MRI studies was retrospectively reviewed. Those with evidence of lateral tunnel pathway narrowing who had both anatomic MRI and phase-contrast MRI at the connection vessels and the ascending aorta were selected for analysis. A total of six patients meeting these criteria were identified, three of whom – A, B, and C – underwent actual stent implantation within 4 months of MRI studies, and were included in the cohort reported by Mets et al.[2] The other three patients – D, E, and F – did not undergo clinical stent implantation, but had computationally simulated stenting based on their MRI-derived anatomy. As noted by Mets et al,[2] there were no standard clinical criteria for stent implantation; rather, a combination of haemodynamic, angiographic, and clinical considerations was usually taken into account. In all patients, MRI anatomic configurations before stent implantation in the total cavopulmonary connection were available. Velocity data before stent implantation were available from phase-contrast MRI at each vessel cross-section for all patients. In patients A, B, and C, anatomies before and after actual stent implantation were also available in the form of angiograms, along with directly measured pressures in the relevant vessels using catheterisation. This analysis was approved by the institutional review boards of the institutions involved.

MRI-derived anatomy

To obtain the anatomy before stent implantation, steady-state free precession transverse MRI images were acquired from the neck to the diaphragm (16–40 slices; pixel spacing 1–1.76 mm; slice thickness 5–7 mm). The MRI images were interpolated and segmented to obtain the three-dimensional surface of the geometries.[11,12] The volume of interest was extracted by trimming planes at the (1) inferior caval vein: downstream of the hepatic venous confluence; (2) superior caval vein: downstream of the junction of the superior caval vein and the innominate vein; and (3) left and right pulmonary arteries: upstream of any branching.

Virtual stent implantation

Due to the non-availability of MRI data after stent implantation, stent size had to be predicted from two 2D angiograms available in coronal and sagittal planes for patients A, B, and C (example shown in Fig 1). The stenotic region was dilated based on the

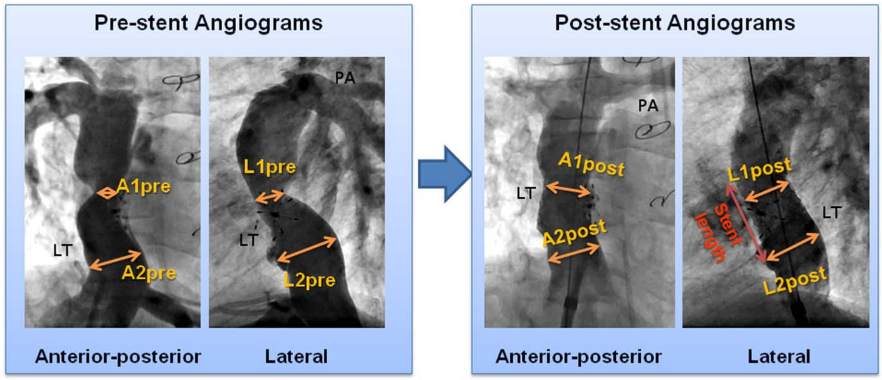

Figure 1.
Examples of angiograms and measurements before (pre-stent) and after (post-stent) stent implantation. LPA = left pulmonary artery; LT = lateral tunnel; RPA = right pulmonary artery; SCV = superior caval vein.

inferior caval vein-to-stenosis diameter ratios obtained from the angiograms to create geometries after stent implantation (Supplement S1). To investigate the effect of stent size, stent diameters of 2-mm increments, which are the commercially available sizes, were created and merged with the MRI-derived geometries (lateral tunnel diameters summarised in Table 1), keeping the stent orientation consistent in the same patient. In cases without actual stent implantation (D, E, and F), stent diameter up to 20 mm was simulated. Simulated stent diameter was not allowed to exceed the diameter of adjacent segments of the lateral tunnel pathway.

Stenosis quantification

The Vascular Modelling ToolKit (VMTK, www.vmtk.org) was used to compute vessel centre lines along the lateral tunnel to estimate its diameter. The stenosis severity for all geometries was quantified by the normalised minimum lateral tunnel diameter, defined as follows:

$$\text{Normalized minimum LT diameter} = \frac{\text{Minimum diameter along the LT}[\text{mm}]}{\text{BSA}[\text{m}^2]}$$

where LT is lateral tunnel and BSA is the patient's body surface area, which was used to account for the difference in patient size.

Haemodynamic assessment of the total cavopulmonary connection

Through-plane phase-contrast MRI slices acquired across all vessels of interest – 40 phases over each cardiac cycle – were segmented[13,14] for each patient. The time-varying velocity fields were integrated over the vessel cross-sectional areas to calculate the associated flow rates. The cycle-averaged flow rates are shown in Table 2. To evaluate the pressure drop and resistance across each patient-specific total cavopulmonary connection, numerical simulations were carried out using an in-house solver.[15,16] To simulate typical and extreme increases in cardiac output during lower-limb exercise, as documented in a recent study of Fontan patients,[17] baseline patient-specific lateral tunnel flow rates were doubled (2×) and tripled (3×),[9] respectively, while preserving the outlet flow ratios as in the baseline condition. As phase-contrast MRI data after stent implantation were not available, patient-specific flow boundary conditions before stent implantation were imposed for all geometries. Time-averaged flow boundary conditions and rigid vessel walls were assumed in all simulations.

Power loss across the connection (E_{loss}), which is defined as the rate of energy dissipated by the blood flowing through the connection, was evaluated from the numerical simulation results. Total cavopulmonary connection resistance (R_{TCPC}), which is the power loss normalised by total systemic return and body surface area, was calculated to compare the energy dissipation across different patient-specific connections:

$$R_{TCPC} = \frac{E_{loss}}{\frac{Qs^2}{BSA}} \left[WU\ (m^2) = \frac{mmHg}{(L/min)} \times m^2 \right]$$

$$E_{loss} = \sum_{n=1}^{s} Q_{inlet,n} \left\{ P_{inlet,n} + \frac{1}{2}\rho \left(\frac{Q}{A}\right)^2_{inlet,n} \right\} - \sum_{n=1}^{2} Q_{outlet,n} \left\{ P_{outlet,n} + \frac{1}{2}\rho \left(\frac{Q}{A}\right)^2_{outlet,n} \right\} [mW]$$

where s is the total number of inlets (s = 3 for Patient F and s = 2 for the rest of the patients), E_{loss} is the

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Table 1. Lateral tunnel diameters.

Patient	A	B	C	D	E	F
Estimated stent diameter from angiogram (mm)	18	14	20	N/A	N/A	N/A
Other stent diameters simulated (mm)	20,22	10,12, 16,18	12,14, 16,18	12,14,16, 18, 20	14,16, 18, 20	14,16, 18,20

Table 2. Phase-contrast MRI segmented flow rates for baseline condition.

Patient	A	B	C	D	E	F
Cardiac output (L/minute)	5.57	3.31	4.83	5.05	3.04	4.49
Total systemic return (L/minute)	3.58	2.51	3.24	4.06	2.60	4.33
LT: SCV: (Left SCV) flow (% of total systemic return)	65:35	41:59	72:28	71:29	58:42	63:17:20
LPA: RPA flow (% total pulmonary outflow)	31:69	38:62	46:54	64:36	30:70	26:74

LPA = left pulmonary artery; LT = lateral tunnel; RPA = right pulmonary artery; SCV = superior caval vein

Total systemic return = sum of the flow rates of the superior and inferior caval veins connected to the connection. The difference between cardiac output and total systemic return is collateral flow, which was not included in the numerical simulations

total cavopulmonary connection power loss, Qs the total systemic return, which is the sum of the flow rates of the superior and inferior caval veins entering the connection, BSA is the body surface area, Q is the flow rate, P is the static pressure relative to the lateral tunnel inlet, ρ is the fluid density (1060 kg/m^3), A is the cross sectional area, inlet is the lateral tunnel or superior caval vein, outlet is the left or right pulmonary artery; WU is the Wood Units

Data analysis

The results before and after stent implantation were compared only in patients A, B, and C, and computational simulations were performed for all patients with various stent diameters. Owing to the small sample size, results of the actual stenting procedures were not evaluated statistically. Modelling of relationships between lateral tunnel diameters and total cavopulmonary connection resistances was performed using non-linear regression, and regression coefficients were determined.

Results

Demographic, anthropometric, and lateral tunnel anatomical data are summarised in Table 3. Available catheterisation data before stent implantation are presented in Table 4.

Comparison of numerical results with catheterisation data

The numerical simulations and the use of flow boundary conditions before stent implantation in all geometries were validated by comparison with pressures measured during catheterisation. In patients A, B, and C, pressure drops across the lateral tunnel stenosis simulated with the numerical simulation tool were consistent with measured data (Fig 2a). Stent implantation reduced the simulated pressure drop across the stenotic region close to 0 mmHg in all three patients.

Effect of stent implantation

Flow patterns. Stream-traces of flow through the lateral tunnel and superior caval vein, colour-coded by velocity magnitude, are presented in Figure 2b. The flow across the stenosis consisted of a high-velocity jet followed by flow re-circulation downstream of the stenosis, which corresponds to the region with the highest pressure drop (Fig 2c). During exercise conditions, the velocity across the lateral tunnel increased and created a much larger pressure drop. After stent implantation, the velocity magnitude of the jet was lowered and the flow was more streamlined along the lateral tunnel pathway under rest and exercise conditions.

Total cavopulmonary connection resistance. Total cavopulmonary connection resistance values for patients A, B, and C were calculated under baseline and exercise conditions (Fig 3). In all three patients, a non-linear increase in total cavopulmonary connection resistance was observed from baseline to increasing exercise levels – increases from baseline were 156–171% at 2× and 327–387% at 3× exercise levels. After stent implantation, the overall resistance values were lower than values without stent implantation, and the increases with exercise were smaller and more gradual – increases from baseline were 47–106% at 2× and 110–239% at 3× exercise levels. Stent implantation lowered the total cavopulmonary connection resistance in all three patients under all conditions, with reductions of

Table 3. Patient demographic, anthropometric, and lateral tunnel anatomic data.

Patient	A	B	C	D	E	F
Age at MRI (years)	15.2	11.6	19.6	14.6*	10.7	14.7
Age at stent (years)	15.2**	11.9	19.6	N/A	N/A	N/A
Body surface area (m^2)	1.57	1.11	1.80	1.43	1.05	1.47
Minimal lateral tunnel diameter (pre-stent) (mm)	10	6	8	9	10	12
Normalised minimum lateral tunnel diameter (pre-stent) (mm/m^2)	6.6	5.4	4.6	6.5	9.1	8.2

Pre-stent = before stent implantation
*MRI was performed under anaesthesia
**Catheterisation was performed under anaesthesia

Table 4. Total cavopulmonary connection pressures, cardiac index, and vascular resistances obtained through catheterisation before stent implantation.

Patient	A	B	C	D	E	F
Inferior caval vein (mmHg)	18	13	16	N/A	17	N/A
Superior caval vein (mmHg)	18	12	14	N/A	17	N/A
LPA (mmHg)	17	11	14	N/A	14	N/A
RPA (mmHg)	17	11	14	N/A	17	N/A
Mean PA wedge (mmHg)	12	9	11	N/A	10	N/A
Cardiac index (L/minute/m^2)	2.1	3.3	3.1	3.4	3.1	3.0
Systemic vascular resistance (iWU)	26.7	13.6	21.3	20.6	18.4	18.0
Pulmonary vascular resistance (iWU)	4.3	1.0	1.3	1.0	1.4	1.6

iWU = indexed Wood's units; LPA = left pulmonary artery; PA = pulmonary artery; RPA = right pulmonary artery

51–84% at rest, 70–88% at 2×, and 70–89% at 3× exercise levels from the original stenotic geometries. Among these three patients, the highest total cavopulmonary connection resistance before stent implantation was in Patient C, which corresponded to the lowest normalised minimum lateral tunnel diameter. The reduction in resistance after stent implantation was also more pronounced at higher exercise levels in this patient.

Effect of stent size. To understand the effect of stenosis severity at baseline and exercise haemodynamics, the results of all six patients and all normalised minimum lateral tunnel diameters were compiled to look for general trends. Figure 4 shows the total cavopulmonary connection resistances of all patients under baseline (Fig 4a) and exercise conditions (Fig 4b and c), with various lateral tunnel diameters. In all cases, the total cavopulmonary connection resistances were reduced by increasing the normalised minimum lateral tunnel diameter. The smallest improvement per unit increase in stent size was observed with the larger normalised minimum lateral tunnel diameter. Using a power law regression, general trends can be found for each condition. When the normalised minimum lateral tunnel diameter was <10 mm/m^2, there was substantial reduction in total cavopulmonary connection resistance with a slight decrease in stenosis severity. For example, from the regression line, resistance reductions from 6 to 8 mm/m^2 were 0.80 WU·m^2 at baseline, 2.38 WU·m^2 at 2×, and 4.13 WU·m^2 at 3× exercise levels. When the normalised minimum lateral tunnel diameter was >10 mm/m^2, the total cavopulmonary connection resistance was much lower, and the same increase in normalised minimum lateral tunnel diameter resulted in smaller improvement in total cavopulmonary connection resistance, where resistance reductions from 12 to 14 mm/m^2 were 0.11 WU·m^2 at baseline, 0.24 WU·m^2 at 2×, and 0.40 WU·m^2 at 3× exercise levels.

In addition, the increase in total cavopulmonary connection resistance with exercise relative to baseline resistance was analysed as a function of normalised minimum lateral tunnel diameter (Fig 4d). It was observed that the relative change in total cavopulmonary connection resistance with exercise was reduced as normalised minimum lateral tunnel diameter increased. When normalised minimum lateral tunnel diameter was 16 mm/m^2, the increase of total cavopulmonary connection resistance from baseline was ~100% at 2× exercise level and 200% at 3× exercise level. This indicates that, at this minimum diameter, the elevation in total cavopulmonary connection resistance due to exercise was almost linear with the increase in exercise level (lateral tunnel flow rate).

Discussion

The goals of this study were to evaluate the effects of lateral tunnel stenosis and stent placement on total cavopulmonary connection haemodynamics at rest and exercise using computational simulation. This framework was applied in six patients with lateral tunnel stenosis as a preliminary investigation to develop criteria for considering intervention and suggest the appropriate stent size for a given patient.

Effect of stent implantation on haemodynamics

Using the numerical simulation results, which were validated with baseline catheterisation data, the

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(a)

Pressure drop across LT stenosis under baseline condition (mmHg)	Patient A		Patient B		Patient C	
	Pre -stent	Post -stent	Pre -stent	Post -stent	Pre -stent	Post -stent
Catheterization	0	0	1	0	2	0
CFD	0.5	0.1	0.8	0.1	1.6	0.1

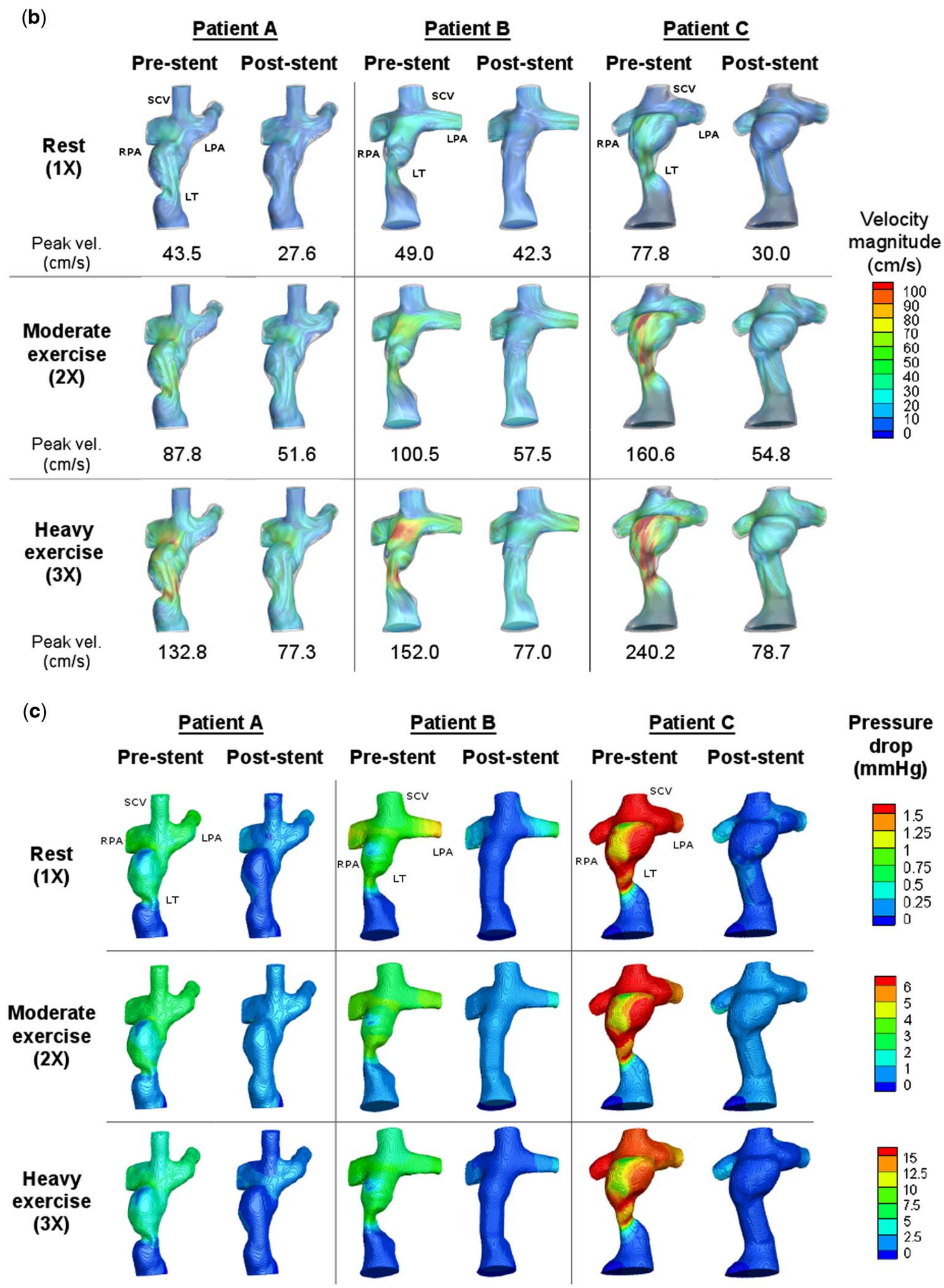

Figure 2.

*(**a**) Comparison between simulated and measured resting pressure drop across the lateral tunnel in patients A, B, and C, who underwent actual stent implantation. (**b**) Colour-coded velocity stream-traces and peak velocities (vel.) and (**c**) pressure drops relative to the lateral tunnel inlet, in patients A, B, and C before (pre-stent) and after (post-stent) stent implantation under baseline (1× lateral tunnel flow rate), moderate (2×), and heavy (3×) exercise conditions. CFD = computational fluid dynamics; LPA = left pulmonary artery; LT = lateral tunnel; RPA = right pulmonary artery; SCV = superior caval vein.*

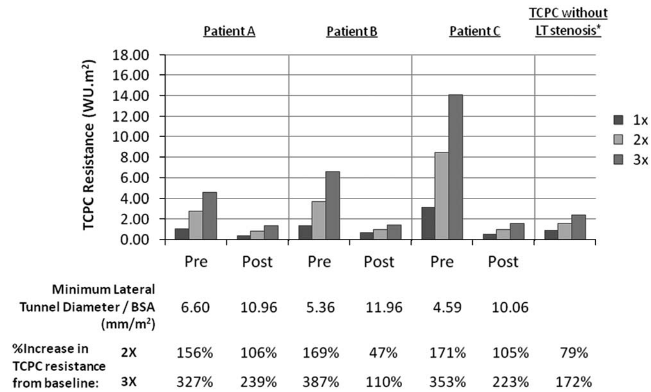

Figure 3.
*Total cavopulmonary connection (TCPC) resistances of patients A, B, and C before and after stent implantation under baseline (1×), moderate (2×), and heavy (3×) exercise conditions. *Average total cavopulmonary connection resistances of patients without apparent lateral tunnel stenosis reported by Sundareswaran et al.[10] BSA = body surface area.*

baseline and exercise haemodynamics in three patients before and after stent implantation were investigated. In a study of 16 patients without apparent total cavopulmonary connection stenosis, Sundareswaran et al[10] estimated the average total cavopulmonary connection resistance to be 0.87 ± 0.58 WU·m^2 at baseline, 1.56 ± 1.00 WU·m^2 at 2× exercise condition, and 2.36 ± 1.62 WU·m^2 at 3× exercise condition. Before stent implantation, patients A, B, and C had total cavopulmonary connection resistances above the average resting resistance of patients in that series. In patient A, there was no measureable pressure gradient across the stenosis under baseline conditions. In patient C, the connection resistance before stent implantation was 1.73 WU at baseline, which was similar in magnitude compared with the patient's pulmonary vascular resistance (1.3 indexed Wood's units), as well as previously reported pulmonary vascular resistance values in Fontan patients (1.3–1.8 WU).[10,18] Thus, although direct measurement may reveal minimal or no pressure gradient across the stenosis, total cavopulmonary connection resistance can still be high in these patients, especially under exercise conditions. This observation illustrates the fact that resting pressure gradients offer only limited insight into the resistance of a total cavopulmonary connection pathway, particularly under the artificial condition of the catheterisation suite, with patients in a supine position and generally under sedation or anaesthesia.

Non-linear increases in power loss and resistance were observed with increasing exercise levels both before and after stent implantation, which are consistent with previous studies;[9] however, the exercise-related increase in total cavopulmonary connection resistance was further exacerbated by the presence of stenosis (Fig 4). Previous studies have demonstrated the relationship between total cavopulmonary connection resistance and various measures of ventricular performance and work,[10] and also the potential link between total cavopulmonary connection energy dissipation and aerobic exercise tolerance.[17] The high total cavopulmonary connection resistance in these patients during exercise would potentially have an adverse effect on single ventricle haemodynamics, and thus contribute to limitations in exercise capacity. After stent implantation, total cavopulmonary connection resistance was reduced in all patients, especially during simulated exercise conditions. Notably, in patients A, B, and C, total cavopulmonary connection resistances after stent implantation under all conditions were below previously reported average patient values.[10]

Summarising the entire study population, a decrease in total cavopulmonary connection resistance can be achieved by increasing normalised minimum lateral tunnel diameter (Fig 4a, b, and c). In addition, the non-linear increase in power loss due to exercise can be alleviated by increasing normalised minimum lateral tunnel diameter (Fig 4d).

Impact of stenosis severity on connection haemodynamics

In view of the patient-specificity for both the total cavopulmonary connection geometry and severity of the stenosis, it is important to identify patients who are likely to benefit from intervention of the lateral tunnel pathway. From the compiled total cavopulmonary connection resistance values of all patients with various normalised minimum lateral tunnel diameters in Figure 4, generalised trends can be observed. Using the best-fit regression lines, we identified threshold of stenosis severity above which stent implantation is likely to result in substantial haemodynamic benefit. Using the regression equation and the average patient values of 0.87 WU·m^2 (baseline), 1.56 WU·m^2 (2× exercise), and

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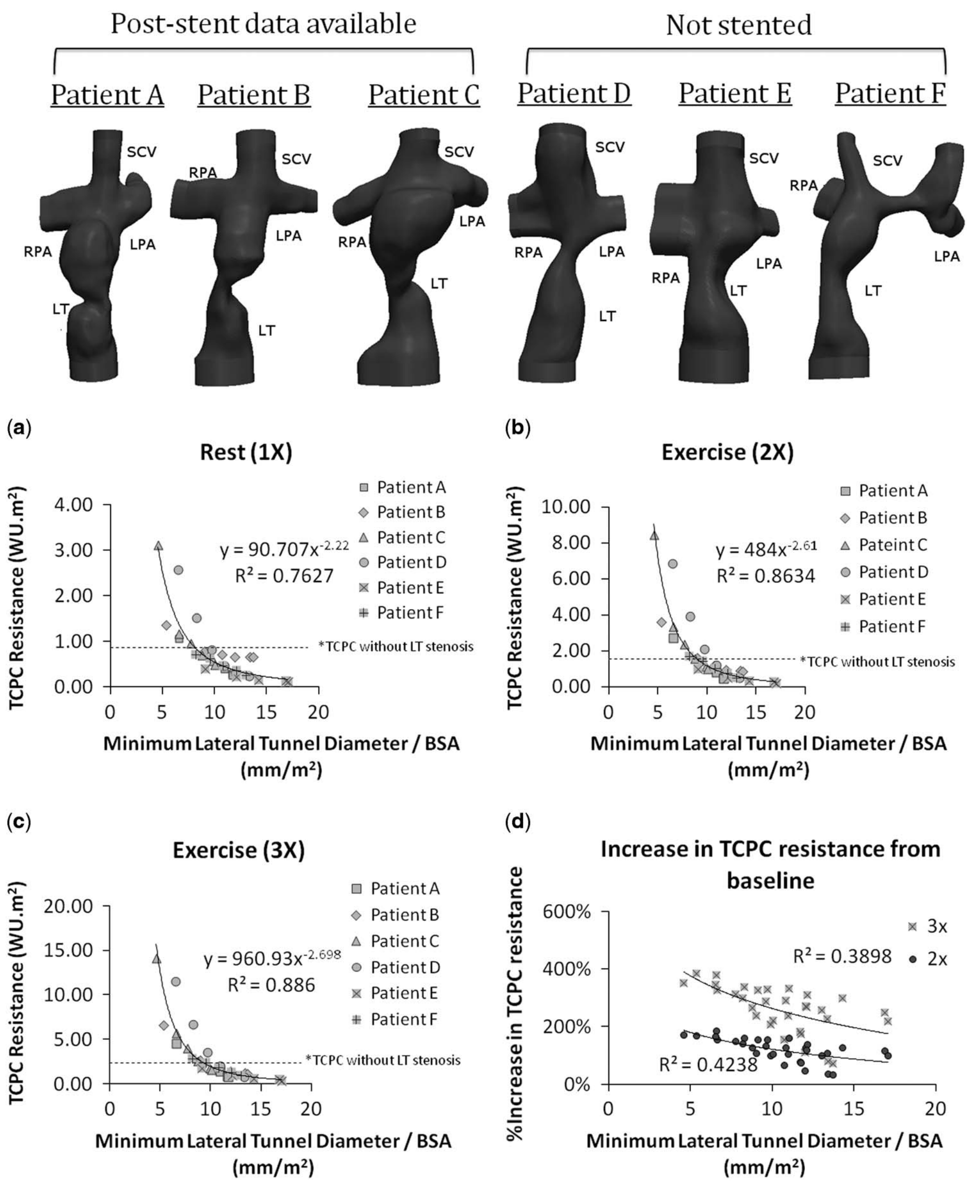

Figure 4.

*Total cavopulmonary connection (TCPC) resistances of all patients at all normalised minimum lateral tunnel diameters simulated under (**a**) baseline (1×), (**b**) moderate (2×), (**c**) heavy (3×) exercise conditions and (**d**) as a function of normalised minimum lateral tunnel diameter. *The dashed lines indicate average total cavopulmonary connection resistances of patients without apparent lateral tunnel stenosis, as reported by Sundareswaran et al.[10] Post-stent = after stent implantation; LPA = left pulmonary artery; LT = lateral tunnel; RPA = right pulmonary artery; SCV = superior caval vein.*

2.36 WU·m^2 (3× exercise), normalised minimum lateral tunnel diameter thresholds of 8.3, 9.0, and 9.3 mm/m^2 were identified for baseline, 2×, and 3× conditions, respectively (Fig 4). When the normalised minimum lateral tunnel diameter was smaller than this threshold, total cavopulmonary connection resistance would be higher than that for a Fontan patient without lateral tunnel stenosis, which may be an appropriate basis for considering intervention. As observed in Figure 4, when the normalised minimum lateral tunnel diameter was <10 mm/m^2, total cavopulmonary connection resistance rose rapidly with increasing severity of stenosis (decreasing diameter) under all conditions. When the normalised minimum lateral tunnel diameter was >16 mm/m^2, further increases in minimum lateral tunnel diameter were estimated to yield little improvement in resistance and stent implantation would likely be of minimal benefit.

Effect of stent size

As shown in a previous study by Mets et al,[2] it is possible to disrupt the baffle during stent expansion

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and cause a baffle leak, highlighting the very real risk of over-dilation. Thus, it seems prudent to aim for a stent size that is sufficient to reduce the total cavopulmonary connection resistance as much as possible, but not so large as to introduce the risk of pathway disruption. As shown in Figure 4, the improvement in total cavopulmonary connection resistance per unit change in stent size decreased with increasing normalised minimum lateral tunnel diameter. When the resulting normalised minimum lateral tunnel diameter was >16 mm/m^2, total cavopulmonary connection resistance was <0.19 WU·m^2 (baseline). For an adult with a BSA of 2.0 m^2, total cavopulmonary connection resistance at baseline with a normalised minimum lateral tunnel diameter of 16 mm/m^2 would be estimated as 0.38 WU, which is much lower than the PVR (0.9–4.3 WU) in average total cavopulmonary connection patients.[10,18] Dilating the lateral tunnel stenosis with stent diameter beyond 16 mm/m^2 was estimated to result in little improvement in total cavopulmonary connection resistance.

Significance

This pilot study evaluated the haemodynamic impact of lateral tunnel stenosis and stent implantation under both resting and exercise conditions using a computational fluid dynamics simulation tool. Preliminary results highlighted the haemodynamic benefit of stent implantation in patients with severe lateral tunnel stenosis, especially during exercise. Simultaneous measurement of pressure gradient across the stenosis during exercise testing in a clinical setting can be challenging. The use of numerical simulations allowed the computation of pressure gradient and connection resistance in various "what-if" scenarios, which can be potentially useful for future interventions.

Reductions in conduit diameter,[19–21] including severe conduit stenosis of up to >50% of diameter,[7] have been reported in extracardiac conduit patients after the Fontan operation. Re-operation for extracardiac conduit stent with implantation of a larger diameter conduit led to improvement in pre-operative symptoms including symptoms of exercise intolerance and protein-losing enteropathy in these patients.[7] If the haemodynamic impact of such re-operations is seen as a function of increased pathway diameter and decreased resistance, the stenosis evaluation framework and results presented in this study may be relevant to extracardiac Fontan patients as well. We hypothesise that, as the extracardiac conduit is made of synthetic graft, the stenosis in extracardiac conduit will be more tubular rather than the discrete stenosis observed in this cohort; however, data for extracardiac conduit stenosis are not available yet, we believe it is still premature to conclude whether they can be treated similarly as intra-cardiac lateral tunnel, which should be addressed in future studies.

Limitations

MRI was not performed after stent implantation; therefore, flow boundary conditions before stent implantation were used for all simulations. The use of such flow boundary conditions has been validated with catheterisation pressure values under resting conditions; however, this assumption is yet to be validated for exercise conditions and vessel flow rate after stent implantation. In addition, catheterisation data after stent implantation are not available. In the future, the use of a lumped parameter model for the rest of the circulation may be useful when coupled to the three-dimensional solver,[22] to help better predict flow boundary conditions for three-dimensional numerical simulations. Other assumptions include the use of steady flow boundary conditions and rigid vessel wall in the numerical simulations of the deformable lateral tunnel pathway, which can affect the simulated haemodynamics. Catheterisation of patient A and MRI of patient D were performed under general anaesthesia. This can potentially affect the blood flow in the Fontan circulation. The respiratory component of Fontan flow dynamics, which may be important both at baseline and during exercise,[23] was not included in the models. In addition, exercise flow rates were prescribed by doubling and tripling baseline lateral tunnel flow, which may not be realistic for patients with a Fontan circulation.[24,25] In a recent cohort of 30 Fontan patients, in whom exercise vessel flow rates at the ventilatory anaerobic threshold were obtained from phase-contrast MRI acquired immediately following lower-leg exercise in the supine position, it was found that total systemic return almost doubled over baseline on average.[17] In one patient, total systemic return nearly tripled. Therefore, a tripled (3×) flow rate condition was included in the present study to simulate this extreme but realistic scenario, which may essentially represent the maximum possible circulatory resistance imposed by the total cavopulmonary connection. Further studies are underway to verify these assumptions.

Although this study aimed to explore general trends by including a patient population with complex and variable total cavopulmonary connection anatomies, the proposed normalised minimum lateral tunnel diameter thresholds for stent implantation or enlargement are preliminary. In addition, we did not examine the possibility of an upper size limit above which further lateral tunnel enlargement was detrimental. In this cohort, discrete stenosis at the lateral tunnel was observed. Tubular or longer segment vessel narrowing may impose different loads and should be investigated in future studies. This analysis ignored the potential impact of other segments of the total cavopulmonary connection, such as pulmonary artery stenosis, which may have an adverse effect on total cavopulmonary connection energy dissipation.[6,26] In the presence of both lateral tunnel and pulmonary artery stenosis, lateral tunnel pathway stent implantation and expansion thresholds may be different. In addition, the clinical relevance of the levels and changes of total cavopulmonary connection resistance investigated in this study is uncertain, although prievious work suggests that rising cavopulmonary pathway resistance leads to progressive adverse impact on various cardiac and vascular functional parameters.[10]

Conclusions

A computational framework for evaluating the haemodynamic impact of lateral tunnel stenosis and stent implantation was developed. Various stent sizes were simulated and pressure gradients and connection resistance were computed. This pilot study evaluated the haemodynamic impact of lateral tunnel stenosis and stent implantation under both baseline and simulated exercise conditions. These analyses demonstrated that stenosis in the lateral tunnel Fontan pathway resulted in higher total cavopulmonary connection resistance than in an unobstructed pathway, and that the elevation in resistance was exacerbated under simulated exercise conditions. Actual and simulated stent implantation enlarged the stenosis and effectively reduced total cavopulmonary connection resistance, but the degree of improvement was related to the stenosis diameter.

Acknowledgement

None.

Financial Support

This study was partially supported by the Wallace H. Coulter Distinguished Faculty Chair funds and by Pre-Doctoral Fellowship Award (13PRE14580005) for Maria Restrepo from the American Heart Association.

Conflicts of Interest

None.

Supplementary material

To view supplementary material for this article, please visit http://dx.doi.org/10.1017/S1047951114002765.

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