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Original Article

Impact of the location of the fenestration on Fontan circulation haemodynamics: a three-dimensional, computational model study

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Abstract *Objectives:* There is no consensus or theoretical explanation regarding the optimal location for the fenestration during the Fontan operation. We investigated the impact of the location of the fenestration on Fontan haemodynamics using a three-dimensional Fontan model in various physiological conditions. *Methods:* A three-dimensional Fontan model was constructed on the basis of CT images, and a 4-mm-diameter fenestration was located between the extracardiac Fontan conduit and the right atrium at three positions: superior, middle, and inferior part of the conduit. Haemodynamics in the Fontan route were analysed using a three-dimensional computational fluid dynamic model in realistic physiological conditions, which were predicted using a lumped parameter model of the cardiovascular system. The respiratory effect of the caval flow was taken into account. The flow rate through the fenestration, the effect of lowering the central venous pressure, and wall shear stress in the Fontan circuit were evaluated under central venous pressures of 10, 15, and 20 mmHg. The pulse power index and pulsatile energy loss index were calculated as energy loss indices. *Results:* Under all central venous pressures, the middle-part fenestration demonstrated the most significant effect on enhancing the flow rate through the fenestration while lowering the central venous pressure. The middle-part fenestration produced the highest time-averaged wall shear stress, pressure pulse index, and pulsatile energy loss index. *Conclusions:* Despite slightly elevated energy loss, the middle-part fenestration most significantly increased cardiac output and lowered central venous pressure under respiration in the Fontan circulation.

Keywords: Fontan; fenestration; computer fluid dynamics; haemodynamics

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The outcome of the Fontan operation has been improved by the introduction of staged operations and various modifications.[1,2] The extracardiac Fontan operation is becoming a standard procedure because of its feasibility in various single-ventricular morphologies and its technical simplicity. Placing a fenestration[3–6] between the extracardiac conduit under conditions of elevated caval pressure enhances cardiac output, and is useful especially in the early postoperative period when the pulmonary vascular resistance is high. A working theoretical explanation of the effect of this fenestration on total haemodynamics, however, has not been proposed. The location of the fenestration differs among surgeons and institutions, and there is no consensus on the most effective location of the fenestration.

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We investigated the effect of the location of the fenestration on Fontan haemodynamics using a three-dimensional multiscale Fontan circulation model.

Materials and methods

Haemodynamics in the Fontan circulation were simulated using a three-dimensional computational fluid dynamic model with an in-house code of the Navier–Stokes equations. This model was coupled with a lumped parameter model of the cardiovascular system to provide realistic physiological boundary conditions at the inlets and outlets.[7–11] A CT scan from a 12-year-old patient who underwent Fontan completion was used. This patient weighed 40 kg and was initially diagnosed with a double-outlet right ventricle, hypoplastic left ventricle, unbalanced atrio-ventricular septal defect, and pulmonary stenosis. Treatment was performed by a fenestrated extracardiac Fontan procedure, following a bicaval cavopulmonary shunt and division of the main pulmonary artery. The size of the conduit was 18 mm, and the fenestration was 4.0 mm in diameter. During surgery, the fenestration was made in the lower part of the conduit as previously reported.[12] A CT scan was performed, and a three-dimensional simulation model was created from the CT slices. A polygon model of the Fontan route was reconstructed and smoothed appropriately; this model comprised a conduit from the inferior caval vein to the pulmonary artery, superior caval vein, and innominate vein.[13] A 4-mm-diameter fenestration hole was placed at the superior, middle, and lower part of the inner curvature of the conduit (Fig 1).

As boundary conditions, the flow rates and pressures at the inlets and outlets were calculated with the lumped parameter model. The flow rates were assigned at the right superior caval vein, innominate vein, and inferior caval vein, whereas the pressures were prescribed at the right and left pulmonary arteries and at the fenestration of the conduit. The vessel wall was treated as approximately rigid; hence, no-slip conditions were used for all velocities. Moreover, to account for the respiratory effect on the Fontan circulation,[14] we further introduced a flow rate at the inlets with consideration of the respiratory effect, which was taken from a previous study by Liu et al.[15] In this condition, the inlet flow from the inferior caval vein, superior caval vein, and innominate vein varied according to the respiratory phase (Fig 2). The density and viscosity of the fluid were 1060 and 0.004 (Pa × s), respectively, and the Reynolds and Strouhal numbers were calculated as 397 and 0.340, respectively.

To evaluate the haemodynamic effect of the fenestration, the following parameters were calculated: blood flow rate through the fenestration, drop rate of central venous pressure secondary to flow through the fenestration, and wall shear stress. Various central venous pressures were used (10, 15, and 20 mmHg) to examine the impact of central venous pressure.

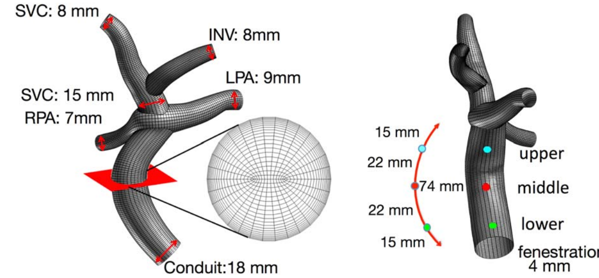

Figure 1.
Polygon model of the fenestrated total cavopulmonary connection. SVC = superior vena cava; RPA = right pulmonary artery; INV = innominate vein; LPA = left pulmonary artery.

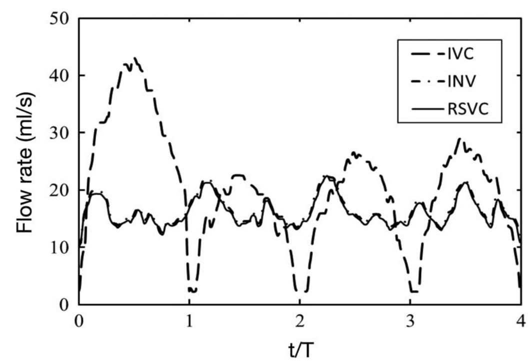

Figure 2.
Flow rate change according to the respiratory phase in inlets. Normalised time (t/T) is expressed as the ratio of time of one cardiac cycle. IVC = inferior vena cava; INV = innominate vein; RSVC = right superior vena cava.

To demonstrate blood energy loss, the pulse power index and the pulsatile energy loss index were calculated[13] as follows:

$$\mathrm{PPI}=\frac{1}{2}\left(1-\frac{\hat{\mathrm{P}}_{\mathrm{A}}}{\hat{\mathrm{P}}_{\mathrm{abs}_{\mathrm{A}}}}\right)$$

where

$$\hat{\mathrm{P}}_{\mathrm{A}}=\frac{\overline{\mathrm{P}}_{\mathrm{A}}}{\mathrm{Q}_{\mathrm{A\ max}}}$$

$$\hat{\mathrm{P}}_{\mathrm{abs}_{\mathrm{A}}}=\frac{\overline{\mathrm{P}_{\mathrm{abs}_{\mathrm{A}}}}}{\mathrm{Q}_{\mathrm{A\ max}}}$$

$$\overline{\mathrm{P}}_{\mathrm{A}}=\frac{1}{\mathrm{T}}\int_0^{\mathrm{T}}\mathrm{P}_{\mathrm{A}}\mathrm{d}t$$

$$\overline{\mathrm{P}_{\mathrm{abs}_{\mathrm{A}}}}=\frac{1}{\mathrm{T}}\int_0^{\mathrm{T}}|\mathrm{P}_{\mathrm{A}}|\mathrm{d}t$$

$$\mathrm{P}_{\mathrm{A}}=\int_{\mathrm{A}}\mathrm{p}(\mathbf{V}\cdot\mathbf{n}_{\mathbf{z}})\mathrm{dA}$$

$$\mathrm{PELI}=2(\mathrm{PPI}_{\mathrm{A2}}-\mathrm{PPI}_{\mathrm{A1}})$$

If the blood flow is stabilised, the pressure pulse index decreases; when the directions of the blood flow fluctuate, the pulse power index increases. The pulsatile energy loss index is the remainder from an arbitrary starting point to a destination; a low pulsatile energy loss index reflects smooth blood flow, meaning less energy loss between the two parts.

This study was approved by the Ethics Committee of The Royal Children's Hospital. Patient consent was waived because of the retrospective nature of the study.

Results

Flow rate through fenestration and lowering rate of central venous pressure

Under a central venous pressure of 19 mmHg, the three models were compared with respect to flow rate through the fenestration and lowering rate of central venous pressure. The middle-part fenestration had the highest flow rate through the fenestration (5.07 ml/s), followed by the inferior-part and superior-part fenestrations (Fig 3a and b). The middle-part fenestration was associated with the highest reduction in central venous pressure (1.37%), although each model had a small effect on decreasing central venous pressure (Fig 3c).

Variations in central venous pressure

A higher central venous pressure was associated with greater blood flow through the fenestration. For every central venous pressure value, the highest blood flow was associated with the middle-part fenestration. With a central venous pressure of 10 mmHg, the blood flow through the fenestration was <1.0 ml/s (Fig 4).

Wall shear stress

Wall shear stress was calculated in every part of the Fontan conduit. The time-averaged wall shear stress was the highest in the middle-part fenestration model (0.44), followed by the superior-part model (0.43). The lower-part model and non-fenestration model exhibited the least wall shear stress (0.39) (Fig 5a and b).

Pulse power index and pulsatile energy loss index

The average pulse power index was the highest in the middle-part model (2.54), followed by the inferior-part model (2.46) and superior-part model (2.23) (Fig 6a). The non-fenestration model had the lowest average pulse power index (2.00). Similarly, the pulsatile energy loss index was the highest in the middle-part model (0.43), followed by the inferior-part model (0.34) and the superior-part model (0.32) (Fig 6b); the non-fenestration model had the smallest pulsatile energy loss index (0.20).

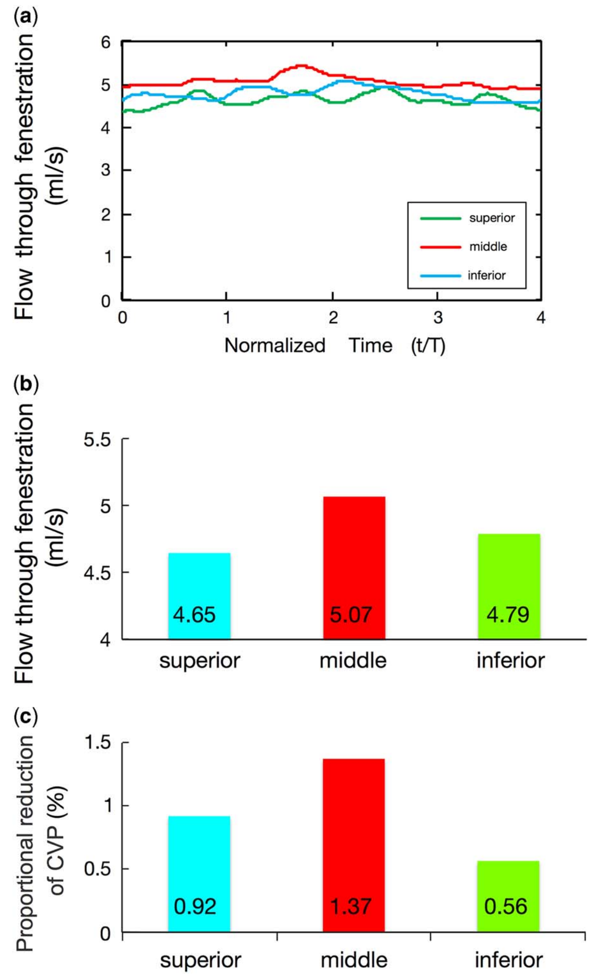

Figure 3.
(a) Blood flow through the fenestration with time. Green: superior fenestration, red: middle fenestration, and blue: inferior fenestration. (b) Average flow rate at central venous pressure of 19 mmHg. (c) Lowering rate of central venous pressure (CVP). Normalised time (t/T) is expressed as the ratio of time of one cardiac cycle. Note the fluctuation of the flow due to the respiratory effect.

Discussion

The surgical outcome of the Fontan procedure has been improved by introduction of modifications such as staged operations,[1,2] a shift from the classic atriopulmonary connection Fontan to an extracardiac total cavopulmonary connection, and improvement in postoperative intensive care management. Placement of a fenestration may ameliorate low cardiac output, and thus lower central venous pressure;[3,5,6,16] however, there is a paucity of knowledge and theoretical understanding about the impact of the fenestration on the Fontan circulation,[5,6,17–19] and whether to

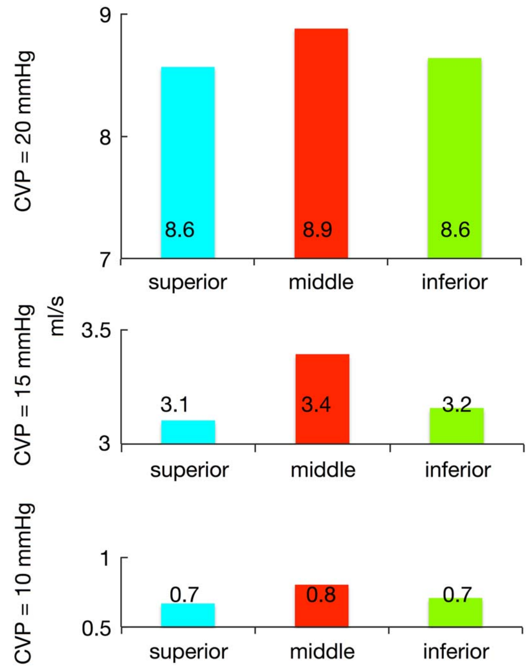

Figure 4.
Blood flow rate through the fenestration. Central venous pressure (CVP) = 20, 15, and 10 mmHg.

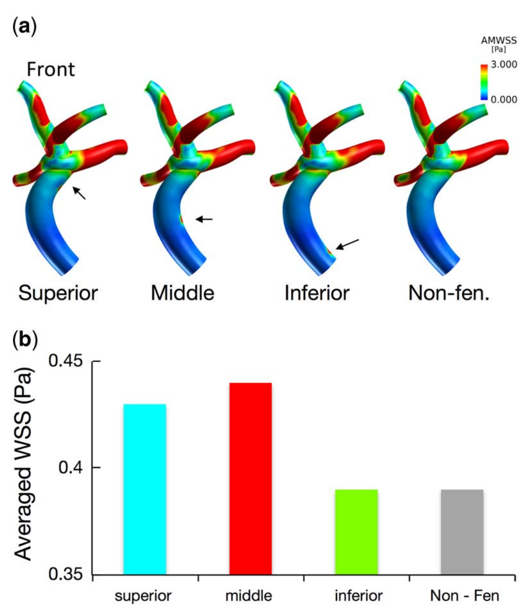

Figure 5.
*(**a**) Wall shear stress (WSS) distribution in Fontan route. Non-Fen: non-fenestrated total cavopulmonary connection; arrow: location of the fenestration. (**b**) Time-averaged wall shear stress.*

place a fenestration often depends upon the surgeon's preference or the institutional policy.[20–22] Although placing a fenestration is beneficial to the Fontan circulation during the early postoperative period in high-risk patients,[16] the fenestration also has drawbacks. Patients with a fenestration may develop

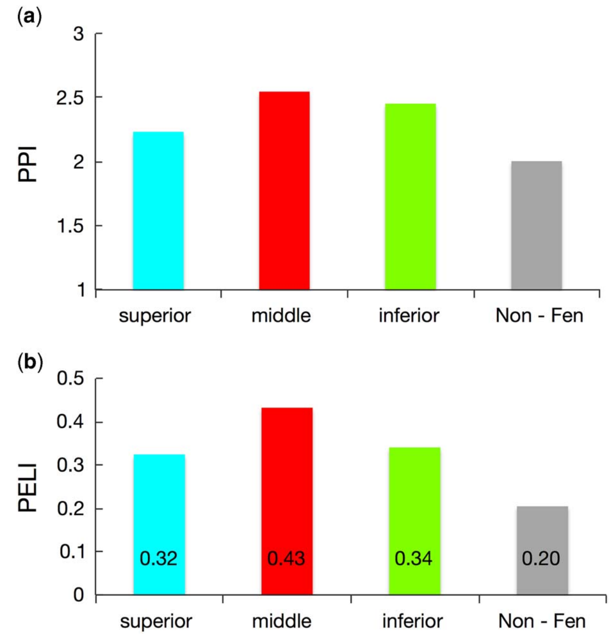

Figure 6.
*(**a**) Averaged pulse power index (PPI). Non-Fen = non-fenestrated total cavopulmonary connection. (**b**) Pulsatile energy loss index (PELI).*

decreased arterial oxygen saturation and a risk for pulmonary and/or systemic thromboembolism.[23,24] In the Fontan circulation, which does not have a pulmonary ventricle, venous flow under low-pressure conditions is driven into the pulmonary artery. Therefore, reducing the energy loss of venous blood flow is important. Previous studies have proven that lower energy loss is essential for more effective Fontan circulation and can be provided with re-configuration of the Fontan route.[25,26] In the present study, we evaluated the impact of the location of the fenestration on the haemodynamics and energy loss in the Fontan circulation. As predicted, blood flow through the fenestration to the systemic atrium increased as central venous pressure increased, and the effect of the fenestration was minimal at a central venous pressure of 10 mmHg. Of the three models with different fenestration locations, blood flow was the highest when the fenestration was located at the middle part of the conduit for every central venous pressure values. Although the middle-part fenestration had the highest blood flow, energy loss according to the pulse power index and the pulsatile energy loss index was the highest, which can represent a trade-off between a benefit and a demerit. An elevated pulse power index and pulsatile energy loss index indicate that the blood flow is fluctuant and turbulent. In the present study, the most turbulent blood flow occurred when the fenestration was located in the middle part of the conduit. Grosse-Wortmann et al[27]

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described blood flow through the fenestration as detected by cardiac MRI; they found that the flow through the fenestration was associated with pulmonary vascular resistance and ventricular diastolic function. They also found that some of the superior caval vein flow was diverted into the fenestration. These findings are consistent with our results: the collision of blood flow from the superior caval vein and inferior caval vein may enhance the flow through the fenestration, but turbulent flow simultaneously increases energy loss. In the early postoperative period, patients who undergo the Fontan procedure often develop low cardiac output, which is treated with a fluid bolus, early extubation to prevent positive airway pressure, and use of nitric oxide to reduce pulmonary vascular resistance. Inotropic support is also necessary to maintain systemic blood pressure and contraction of the ventricle. Inotropes may also complement these energy losses caused by the fenestration. The central venous pressure-lowering effect in this study was subtle; even the middle-part fenestration reduced central venous pressure by only 1.7%. This result suggests that we cannot expect placement of a fenestration to effectively reduce central venous pressure. Inhalation of nitric oxide or vasodilators may have a more significant effect on lowering pulmonary vascular resistance, leading to a lower central venous pressure.

There are several limitations to this study: one is that the entire study involved only a single patient who underwent a fenestrated extracardiac Fontan procedure because, during the study period, this patient was the only one who had undergone a postoperative CT scan; and another limitation is that the vessel wall was a solid model. Although the haemodynamic parameters interact and influence one another, as also shown in our previous reports,[8,9,28] we used a modified three-dimensional Fontan circulation model to focus on the effect of the fenestration in this study. Although multifactorial components such as pulmonary vascular resistance and collateral flow into the pulmonary artery can influence central venous pressure, as well as ventricular contraction, diastolic function, or atrioventricular valve regurgitation, we simplified the model by setting the central venous pressure at 10–20 mmHg. The boundaries were referenced from previous reports to involve the respiratory effect on the Fontan circuit.

Conclusions

The fenestration at the middle part of the conduit exhibited the highest amount of blood flow through the fenestration, despite the largest energy loss and highest wall shear stress. The higher blood flow through the fenestration may represent a trade-off for the increased energy loss.

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Conflicts of Interest

None.

Ethical Standards

The authors assert that all procedures contributing to this work comply with the ethical standards of the relevant national guidelines on human experimentation (National Statement on Ethical Conduct in Human Research) and with the Helsinki Declaration of 1975, as revised in 2008, and has been approved by the institutional committees (The Human Research Ethics Committee of the Royal Children's Hospital).

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