CFD study of physiological Fontan circulation

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1. Introduction

Approximately 1% of newborn babies present some form of congenital heart defect (CHD), with as much as half of these undergoing surgery in their lifetime [1]. The most severe malformations are treated with palliative surgery, the most common of which is the so-called Fontan circulation.

The conventional Fontan circulation deviates the superior vena cava (SVC=1/3 of the systemic venous return) towards the right lung (3/5 of total lung volume) and the inferior vena cava (IVC=2/3 of the systemic venous return) towards the left lung (2/5 of total lung volume). A "physiological" Fontan deviating the SVC towards the left lung and the IVC towards the right lung was compared with the conventional setting by computational fluid dynamics (CFD), studying if this setting achieves a more favourable hemodynamic than the conventional Fontan circulation.

2. Methods

An *in-silico* three-dimensional (3D) parametric model of the physiological Fontan circulation was developed with the positions of the SVC and IVC connections varied along the pulmonary arteries (Figure 1). Idealized vascular geometries were constructed with constant dimensions of SVC, IVC, and right and left pulmonary arteries. Steady velocity inflows for IVC and SVC and constant equal outflow pressures for right and left pulmonary arteries were set accordingly to established literature reports, to obtain finite-volume incompressible steady flow simulations, assuming a single-phase, Newtonian, isothermal, laminar blood flow. The key reference data for dimensioning the vascular geometry were a 3.5 year-old patient, body weight 16 kg, height 98 cm, body surface area 0.65 m^2, and total cardiac output 2.6 L/min, with an indexed cardiac output = 4 L/min/m^2. Figure 1 shows a preliminary result obtained on two idealized vascular geometries, which model, respectively, the conventional and physiological Fontan connection. The pulmonary artery (PA) length ℓ, measured as the straight-line distance between the first branching of right and left pulmonary arteries, was 7.3 cm. Figure 1 (top) shows the conventional Fontan circulation model, with the SVC confluence at 0.9 ℓ from the left pulmonary artery and the IVC at 0.6 ℓ from the left pulmonary artery, with a right-angle (90°) connection for the SVC and a 75° connection facing towards the left pulmonary artery for the IVC. This is taken as the baseline configuration for comparison purposes. Figure 1 (bottom) shows one sample of a physiological Fontan circulation parametric model. In this parametric model, the IVC confluence was varied over the range $0.77\,\ell \leq x \leq 0.92\,\ell$ from the first branching of the left pulmonary artery. The IVC confluence angle with the pulmonary artery was varied with 15° increments between 60° and 90°. The SVC was connected to the pulmonary artery at a fixed angle of 60°.

3. Results and discussion

Energy loss rates for all the 21 tested configurations are reported in Table 1. The physiological Fontan, with the IVC angle of confluence of 60° and centerline confluence $x = 0.88\,\ell$ is the configuration that has comparatively the lowest energy loss rate among the 21 variants considered in this study. Hence this configuration, which is depicted in Figure 1 (bottom) is singled out as the preferred configuration, and compared to the conventional Fontan of Figure 1 (top). The comparison of the physiological versus conventional Fontan provided these results: 1) mean IVC pressure 13.9 mmHg versus 14.1mmHg (= 0.2 mmHg reduction); 2) energy loss rate 5.55mW versus 6.61 mW (= 16% reduction); 3) kinetic energy 283 J/m^3 versus 396 J/m^3 (= 29% reduction).

3. Outlook

Topically, the workflow for patient-specific *in silico* hemodynamic analysis involves a number of steps, from data assimilation, image processing, mesh generation, problem set-up, and simulation, requiring extensive manual intervention. This is particularly true for the univentricular circulation, given the variability of patient's conditions and morphologies.

A more automated meshing-solution step will be explored by new finite element methods based on extremely general partitions of the computational domain. The new approach is based on a recent extension of the applicability of the interior-penalty discontinuous Galerkin (dG) method to meshes comprising extremely general, essentially arbitrarily-shaped element shapes [3]. This approach requires some computational overhead in the set-up of the discrete problem, but provides a discretisation that is very robust under mesh distortion. It is shown how the flexibility of the approach can be used to produce a novel numerical multiscaling approach.

4. Conclusions

A more physiological flow distribution is accompanied by a reduction of mean IVC pressure and by substantial reductions of the energy loss rate and of peak kinetic energy. The potential clinical impact of these hemodynamic changes in reducing the incidence and severity of the adverse long-term effects of the Fontan circulation, in particular liver failure and protein-losing enteropathy, still remains to be assessed and will be the subject of future work.
A proof-of-concept use of general mesh finite element methods is presented, to facilitate the turnaround of patient-specific simulations in future *in-silico* simulations of the physiological Fontan.

5. Acknowledgements

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	$\theta = 60°$	$\theta = 75°$	$\theta = 90°$
$0.77\,\ell$	5.66	5.94	6.02
$0.78\,\ell$	5.70	5.91	6.12
$0.81\,\ell$	5.55	5.80	5.79
$0.85\,\ell$	5.57	5.75	5.96
$0.88\,\ell$	5.71	5.91	6.08
$0.91\,\ell$	5.84	5.98	6.10
$0.92\,\ell$	5.88	6.01	6.19

Table 1: Energy loss rate from 21 configurations of "physiological" Fontan as predicted by CFD, for different positions of the IVC to PA confluence given as a percentage of the length of the pulmonary artery ℓ and for different SVC to PA angles θ.

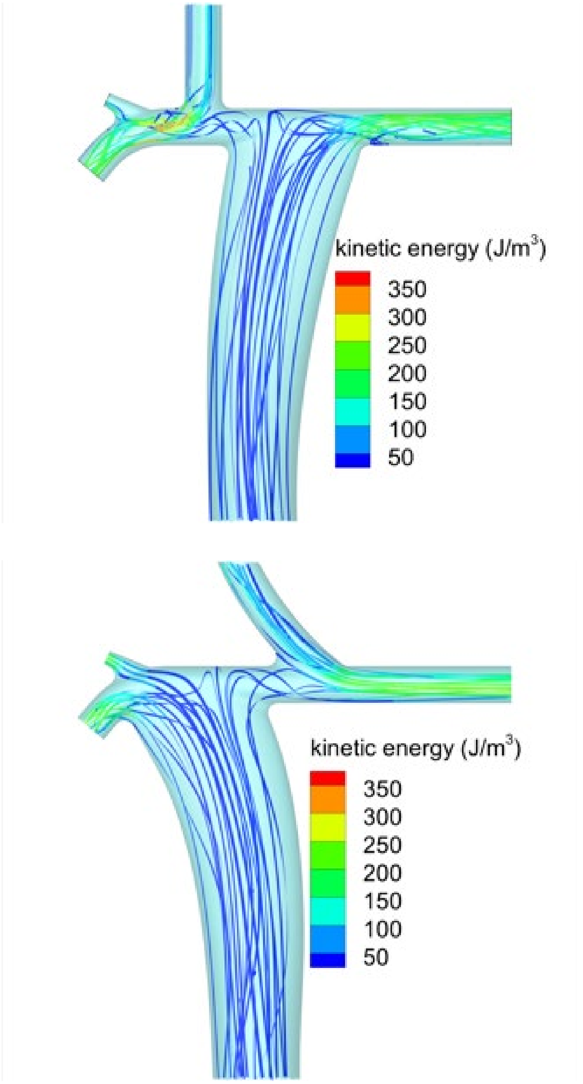

Figure 1: Conventional (top) versus physiological (bottom) Fontan circulation.

6. References

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