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Technical note

Tailoring the hybrid palliation for hypoplastic left heart syndrome: A simulation study using a lumped parameter model

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ABSTRACT

The results of Hybrid procedure (HP) for the hypoplastic left heart syndrome (HLHS) depend on several variables: pulmonary artery banding tightness (PAB), atrial septal defect size (ASD) and patent ductus arteriosus stent size (PDA). A HP complication could be the aortic coarctaction (CoAo). The reverse Blalock–Taussig shunt (RevBT) placement was proposed to avoid CoAo effects. This work aims at developing a lumped parameter model (LPM) to investigate the effects of the different variables on HP haemodynamics. A preliminary verification was performed collecting measurements on a newborn HLHS patient to calculate LPM input parameters to reproduce patient's baseline. Results suggest that haemodynamics is affected by ASD (ASD: 0.15–0.55 cm, pulmonary to systemic flow ratio Q_p/Q_s: 0.73–1, cardiac output (CO): 1–1.5 l/min and ventricular stroke work SW: 336–577 ml mmHg) and by the PAB diameter (PAB: 0.07–0.2 cm, Q_p/Q_s: 0.46–2.1, CO: 1.3–1.6 l/min and SW: 591–535 ml mmHg). Haemodynamics was neither affected by RevBT diameter nor by PDA diameter higher than 0.2 cm. RevBT implantation does not change the HP haemodynamics, but it can make the CoAo effect negligible. LPM could be useful to support clinical decision in complex physiopathology and to calibrate and personalise the parameters that play a role on flow distribution.

1. Introduction

The management of HLHS with the HP is challenging as it depends on several variables [1,9]. In fact, Q_p/Q_s depends on the PDA dimensions, PAB tightness, ASD dimension, systemic and pulmonary resistances regulation in the post operative management [[1,2,6],[9–11],[14],[18–20]]. Additionally, the coronary and cerebral circulations depend on retrograde perfusion assured by the PDA stent [19]. The placement of a RevBT was proposed to maintain the coronary and brain perfusion in patients with limited/absent anterograde flow from the left ventricle, high risk of CoAo development after the HP, hypoplastic aorta [[2,9,14],[18–20]].

Computational modeling could be helpful in this complex scenario as it was done so far based on computational fluid dynamics (CFD) or multiscale approaches [[4–6],[10],[18–20]]. This work aims at integrating this approach using LPM of the cardiovascular system as it was recently done [22]. In this paper we merge the effects on HP haemodynamics of: ASD size, PAB tightness, PDA stent size, RevBT diameters and RevBT placement in the presence of CoAo.

Abbreviations: Cao1, aorta1 compliance; Cao2, aorta 2 compliance; Rao2, aorta 2 resistance; CoAo, aortic coarctaction; Pao1, aortic 1 pressure; Pao2, aortic 2 pressure; Cap, arterial pulmonary compliance; Cas, arterial systemic compliance; Rap, arterial pulmonary resistance; Ras, arterial systemic resistance; ASD, atrial septal defect size; CO, cardiac output; CVP, central venous pressure; CFD, computational fluid dynamics; EF, ejection fraction; HR, heart rate; HP, hybrid procedure; HLHS, hypoplastic left heart syndrome; Civc, inferior vena cava compliance; Pivc, inferior vena cava pressure; Rvcs, inferior vena cava resistance; Pt, intrathoracic Pressure; Pla, left atrial pressure; Clpa, left pulmonary arterial compliance; Plpa, left pulmonary arterial pressure; Rlpa, left pulmonary artery resistance; Rlpv, left pulmonary vein resistance; Clb, lower body compliance; Pas_lb, lower body pressure; Rlb, lower body resistance; LPM, lumped parameter model; PDA, patent ductus arteriosus; PAB, pulmonary artery banding; Pap, pulmonary arterial pressure; Q_{pulm}, pulmonary flow; Q_p/Q_s, pulmonary to systemic flow ratio; Rap, pulmonary trunk resistance; Cap, pulmonary trunk compliance; Rri, pulmonary valve resistance; RevBT, reverse Blalock–Taussig shunt; Pra, right atrial pressure; Crpa, right pulmonary arterial compliance; Prpa, right pulmonary arterial pressure; Rrpa, right pulmonary artery resistance; Rrpv, right pulmonary vein resistance; CORV, right ventricular cardiac output; Ervs, right ventricular end diastolic elastance; Ervd, right ventricular end sistolic elastance; RVEDV, right ventricular end diastolic volume; RVESV, right ventricular end sistolic volume; Prv(D), right ventricular diastolic pressure; Prv(S), right ventricular systolic pressure; Qlb_S, systolic peak flow in the lower body; Qub_S, systolic peak flow in the upper body; Csvc, superior vena cava compliance; Psvc, superior vena cava pressure; Rsvc, superior vena cava resistance; AoP/Pas, systemic arterial pressure; Rri, tricuspid valve resistance; Cub, upper body compliance; Pas_ub, upper body pressure; Rub, upper body resistance; SW, ventricular stroke work.

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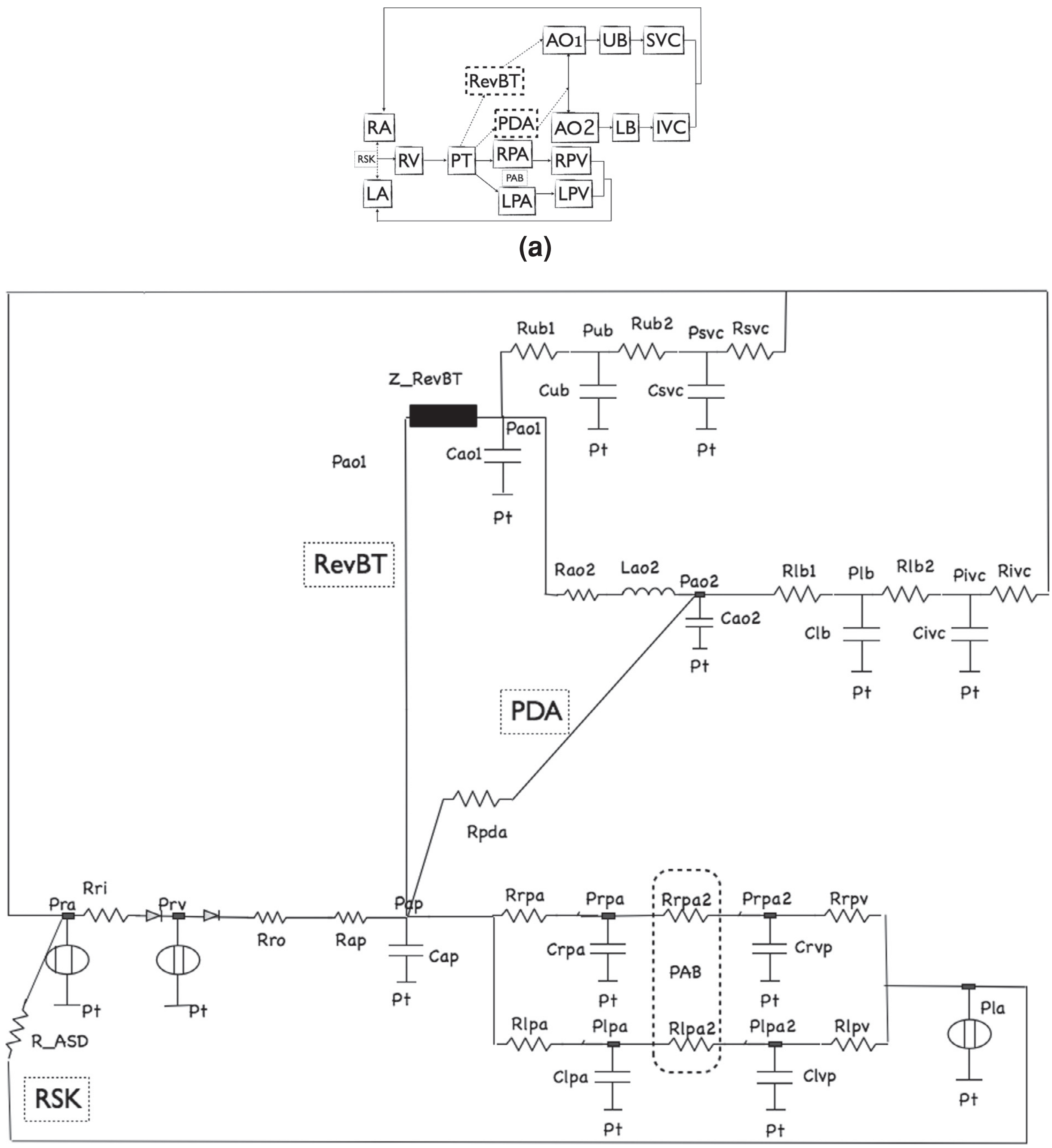

(b)

Fig. 1. (a) Schematic block representation of the cardiovascular system of a hypoplastic left heart syndrome patient. RA (LA): right (left) atrium, RV: right ventricle, PT: pulmonary trunk, RPA (LPA): right (left) pulmonary artery, RPV (LPV): right (left) pulmonary veins, AO1 (AO2): ascending aorta and aortic arch (thoracic and abdominal aorta), UB (LB): upper (lower) body circulation, SVC (IVC): superior (inferior) vena cava. Dashed lines and blocks represent the surgical procedures: Rashkind septostomy (RSK), pulmonary artery banding (PAB), patent ductus arteriosus (PDA) stenting, reverse Blalock–Taussig (RevBT) implantation. (b) Electrical analogue of the cardiocirculatory system in hypoplastic left heart syndrome patient underwent hybrid palliation and RevBT shunt placement. Pra (Prv): right atrial (ventricular) pressure, Pt (Pla): intrathoracic (left atrial) pressure, Pap: pulmonary arterial pressure, Prpa (Plpa): right (left) pulmonary arterial pressure, Pao1 (Pao2): aortic 1 (aortic 2) pressure, Pas_ub (Pas_lb): upper (lower) body pressure, Psvc (Pivc): superior (inferior) vena cava pressure, Rri (Rro): tricuspid (pulmonary) valve resistance, Rap: pulmonary trunk resistance, Rrpa (Rlpa): right (left) pulmonary artery resistance, Rrpv (Rlpv): right (left) pulmonary vein resistance, Rao2: aorta2 resistance, Rub (Rlb): upper (lower) body resistance, Rsvc (ivc): superior (inferior) vena cava resistance, Cap: pulmonary trunk compliance, Crpa (Clpa): right (left) pulmonary arterial compliance, Cao1 (Cao2): aorta1 (aorta2) compliance, Cub (Clb): upper (lower) body compliance, Csvc(Civc): superior(inferior) vena cava compliance. Dashed boxes represent the surgical procedures.

2. Materials and methods

A LPM of the cardiovascular system [7] was adapted to HLHS (Fig. 1a) where the systemic and the pulmonary circulation are sustained by the right ventricle which ejects in the pulmonary arteries, while the systemic flow is assured by the PDA. LPM is divided into different sections [7,16]: heart chambers, represented by variable elastance models; systemic and pulmonary sections represented by Windkessel models. The PDA is modeled as a resistance (Rpda) between the pulmonary trunk and the descending aorta. The ASD is modeled as a resistance (R_ASD) between the left and the right atrium. The model is implemented in Labview 7.1 (National