

The role of additional pulmonary blood flow in the cavopulmonary anastomosis

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Abstract—The bidirectional cavopulmonary anastomosis (BCPA) is an operation often performed on children with functionally single ventricles, and is meant to prepare a future total cavopulmonary anastomosis. In the circulation ensuing from a BCPA, the lower circulation is external to the lung perfusion, with a propensity to low oxygen saturation, being only oxygenated by the mixing with the blood from the pulmonary veins, in the right atrium. A study is presented of the role of an additional pulmonary blood flow on the oxygen saturation, by means of a lumped parameter model.

Keywords— Cardiac surgery, congenital heart disease, univentricular circulation, mathematical modelling

I. INTRODUCTION

SINCE many years, patients with only one functional ventricle (the so-called univentricular patients) are operated on with one (or more, in various stages at different patient's ages) of a series of surgical operations. The bidirectional cavopulmonary anastomosis (BCPA) is one of these, principally meant to prepare a future total cavopulmonary anastomosis, i.e., the connection with the two vene cavae connected directly to the pulmonary arteries. This connection is particularly important in the treatment of hypoplastic left heart syndrome (HLHS), when the functional right ventricle must be gradually prepared to bear the load associated to the circulation [1].

The circulation after the BCPA is basically composed of two circuits in parallel, the upper and the lower circulation, the latter being external to the lung perfusion. Hence, there is a potential problem of low oxygen saturation: the lower circulation is only oxygenated by the mixing with the blood from the pulmonary veins, in the right atrium (RA), hence the blood in the inferior part of the systemic circulation can be hypooxygenated, especially during exercise conditions. It has been proposed that an additional pulmonary blood flow, such as that imparted by a modified Blalock-Taussig shunt (which derives a fraction of the blood from the subclavian artery to the pulmonary arteries) could be beneficial as for the oxygen saturation [2]. In the present study, this hypothesis is verified by means of a lumped parameter model, which is a generalization of that proposed in [3].

II. MATERIALS AND METHODS

With reference to the modelling of the BCPA proposed by Santamore et al. [3], suitable modifications can be provided to account for the presence of an additional contribution to the pulmonary flow, such as that imparted by a Blalock-Taussig shunt.

For the total oxygen consumption \dot{V}_{O_2} , it can be stated that

$$\dot{V}_{O_2} = k\dot{V}_{O_2} + k_s\dot{V}_{O_2} + (1-k-k_s)\dot{V}_{O_2} \quad (1)$$

k being the fraction of the whole body oxygen consumption relative to used by the upper body, while k_s is the fraction of the same quantity which can be attributed to the part of the circulatory system constituted by the shunt. Eq. (1) states that the oxygen consumption in the lower body is $(1-k-k_s)\dot{V}_{O_2}$.

It is natural to assume that $k_s \cong 0$.

The rate of oxygen supply in the IVC and SVC is given by Eqs. 2 and 3, respectively:

$$C_{a,O_2} Q_{IVC} - (1-k)\dot{V}_{O_2} = C_{IVC,O_2} Q_{IVC} \quad (2)$$

$$C_{a,O_2} Q_{SVC} - k\dot{V}_{O_2} = C_{SVC,O_2} Q_{SVC} \quad (3)$$

These formulas relate the oxygen content in the aorta, C_{a,O_2} , and the rate of oxygen consumption in the whole body, \dot{V}_{O_2} , to the oxygen content in the lower and upper body circulation, C_{IVC,O_2} and C_{SVC,O_2} respectively.

Since the pulmonary flow is given in this case by two contributions, the following formula applies:

$$Q_P = Q_{SVC} + Q_{shunt} \quad (4)$$

where Q_{shunt} is the flow rate across the shunt connecting the aorta and the PAs.

In the usual BCPA, i.e., without additional sources of pulmonary blood flow, the mass conservation in Eq. (4) is simplified as $Q_P = Q_{SVC}$. The balance of oxygen content in the pulmonary circulation leads to

$$C_{SVC,O_2} Q_{SVC} + C_{shunt,O_2} Q_{shunt} + \dot{V}_{O_2,L} = C_{PV,O_2} Q_P \quad (4b)$$

The combined cardiac output can be expressed as

$$CO = Q_{IVC} + Q_{SVC} \quad (5)$$

In a steady state, the oxygen provided by the lungs is equal to that consumed in the body, i.e.,

$$\dot{V}_{O_2,L} = \dot{V}_{O_2} \quad (6)$$

From Eq. (4b), after substitution of the term $C_{SVC,O_2} Q_{SVC}$ with the right-hand side of Eq. 3,

$$C_{a,O_2} Q_{SVC} - k\dot{V}_{O_2} + C_{shunt,O_2} Q_{shunt} + \dot{V}_{O_2,L} = C_{PV,O_2} Q_P$$

Since $C_{shunt,O_2} = C_{a,O_2}$, this equation can be rewritten as

$$\begin{aligned} C_{a,O_2} (Q_{SVC} + Q_{shunt}) + (1-k)\dot{V}_{O_2} \\ = C_{PV,O_2} (Q_{SVC} + Q_{shunt}) \end{aligned} \quad (7)$$

In the derivation, use has been made of Eq. (6).

From Eq. (7) we can write the following expression, useful to derive the oxygen delivery to the arterial system:

$$C_{a,O_2}(CO + Q_{shunt}) = C_{PV,O_2}(CO + Q_{shunt}) - (1-k)\dot{V}_{O_2} + C_{a,O_2}Q_{IVC} - C_{PV,O_2}Q_{IVC} \quad (8)$$

Dividing Eq. (7) by $(Q_{SVC} + Q_{shunt})$ and multiplying it by Q_{IVC} , we derive the formula:

$$(C_{a,O_2} - C_{PV,O_2})Q_{IVC} = -(1-k)\dot{V}_{O_2} \frac{Q_{IVC}}{Q_{SVC} + Q_{shunt}} \quad (9)$$

Plugging this expression for $(C_{a,O_2} - C_{PV,O_2})Q_{IVC}$ in the right-hand side of Eq. (8), the following formula can be straightforwardly derived:

$$C_{a,O_2}(CO + Q_{shunt}) = C_{PV,O_2}(CO + Q_{shunt}) - (1-k)\dot{V}_{O_2} \frac{1+x}{x} \quad (10)$$

where the position $x \equiv \frac{Q_{SVC} + Q_{shunt}}{Q_{IVC}}$ has been made.

In order to evaluate the effect of the systemic-to-pulmonary shunt, we assume in the following that $Q_{shunt} = \beta CO$, hence different degrees of shunting will be considered, by means of the choice of β .

From Eq. 10, the value of systemic oxygen delivery ($C_{a,O_2} \times CO$) can be immediately derived.

III. RESULTS

The results of changing the parameter β (i.e., the fraction of the CO which is driven into the systemic-to-pulmonary shunt) in the model point out that there is an overall improvement in blood oxygen saturation level, either globally or at the regional (IVC or SVC) level, for increasing values of β . The values for the SVC/IVC ratio in the figures hereby reported are in the physiological range (Q_{SVC}/Q_{IVC} comprised between 35/65 and 65/35), as in [4].

In particular, Fig. 1 reports the global blood oxygen saturation level, which increases with Q_{SVC}/Q_{IVC} , for every value of the shunt parameter β . This is expected, since higher SVC flows entail a higher pulmonary perfusion, as per Eq. 4. It is evident that increasing β , at a given value of the ratio Q_{SVC}/Q_{IVC} , improves the blood oxygen saturation level, especially at the lower Q_{SVC}/Q_{IVC} values. This result is remarkable especially for exercise conditions, when the lower body consumes a higher volume of oxygen than the upper body.

Also for the regional blood oxygen saturation level the presence of additional blood flow is beneficial. Fig. 2 shows the IVC oxygen saturation as a function of Q_{SVC}/Q_{IVC} and β . A marked improvement is observed, especially for the minimum physiological value of Q_{SVC}/Q_{IVC} in Fig. 2, allowing the oxygen saturation in the lower circulation to reach over 70% (for $\beta=0.3$), from 60% in absence of additional pulmonary flow.

A similar improvement, even though of smaller degree, was observed also for the SVC compartment.

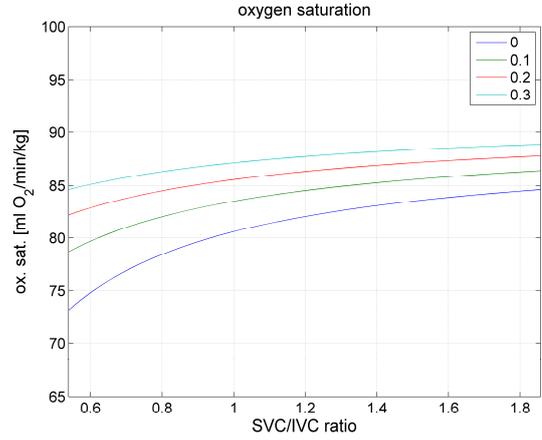


Figure 1: Oxygen saturation vs. SVC/IVC ratio, as a function of the parameter β , which characterizes the systemic-to-pulmonary shunt.

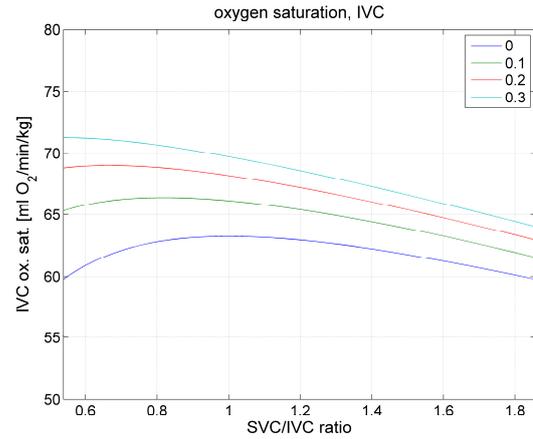


Figure 2: IVC oxygen saturation vs. SVC/IVC ratio, as a function of the parameter β , which characterizes the systemic-to-pulmonary shunt.

The observed advantages of providing an additional source of pulmonary blood flow, such as the modified Blalock-Taussig shunt, after BCPA are substantially in accordance with recent reports of a retrospective study with a remarkable sample size (82 patients) [5].

This mathematical model can presumably be used in the future to optimize the management of the pediatric patients with a single functional ventricle, from birth to the final surgical stage, the TCPC, i.e., total cavopulmonary connection.

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