Additional Pulmonary Blood Flow in the Cavopulmonary Anastomosis by Means of a Modified Blalock-Taussig Shunt
Is It a Beneficial Clinical Option?

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Abstract: Since many years, patients with functionally single ventricles are subjected to surgical operations, meant to create a more favourable haemodynamics. The bidirectional cavopulmonary anastomosis (BCPA) is one of such operations, and is principally meant to prepare a future total cavopulmonary anastomosis, i.e., the direct connection of the two vene cavae to the pulmonary arteries. Since the circulation ensuing from a BCPA is basically composed of two circuits in parallel, the upper and the lower circulation, the latter being external to the lung perfusion, there is a potential problem of low oxygen saturation. It has been proposed that an additional pulmonary blood flow, such as that imparted by a modified Blalock-Taussig shunt could be beneficial as for the oxygen saturation. In the present study, this hypothesis is verified by means of a lumped parameter model, considering different degrees of shunting. The results support the view that an additional source of blood flow can have a beneficial effect on the pediatric patient operated on with a BCPA. Future comparison of numerical results with actual clinical data will allow to evaluate the predictive capabilities of the model.

1 INTRODUCTION

Since many years, patients with functionally single ventricles are operated on with one (or more, in various stages at different patient's ages) of a series of surgical operations. In fact, these patients present congenital hindrances to the normal circulation, undermining the physiological circulation and tissue oxygenation. The bidirectional cavopulmonary anastomosis (BCPA) is one of the operations dealing with the treatment of such patients, and is 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 (Goldberg and Gomez, 2003).

Since the circulation ensuing from a BCPA is basically composed of two circuits in parallel, the upper and the lower circulation, the latter being external to the lung perfusion, 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 could be beneficial as for the oxygen saturation (Caspi et al., 2003). This hypothesis needs to be put to test in clearly controllable conditions, such as those provided by a mathematical model of the circulation. In the present study, the beneficial role of an additional pulmonary blood flow is tested by means of a lumped parameter model, which is a generalization of that proposed by (Santamore et al., 1998).

The effects of various degrees of shunting are discussed, in order to evaluate whether such an operation actually constitutes an advantage over the traditional BCPA. The model of the operation has not yet been validated with a point-to-point comparison with clinical data, but the clinical reports available in the literature allow at least a qualitative assessment of the model.

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2 MATERIALS AND METHODS

With reference to the modelling of the BCPA proposed by Santamore et al., 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. Fig. 1 presents an instance of this operation, meant to increase pulmonary blood flow by surgical means.

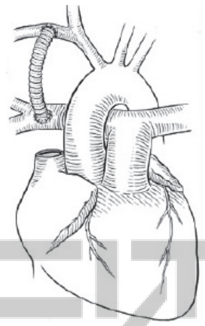

Figure 1: The modified Blalock-Taussig shunt is meant to enhance the pulmonary flow, by deriving a fraction of the blood from the subclavian artery to the pulmonary arteries (figure downloaded from http://upload.wikimedia.org/wikipedia/commons/thumb/6/63/Blalock_shuntWiki.jpg/220px-Blalock_shuntWiki.jpg).

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

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

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. (1a) states that the oxygen consumption in the lower body is $(1-k-k_s)\dot{V}_{O_2}$. It is natural to assume that $k_s \cong 0$, so that

$$\dot{V}_{O_2} = k\dot{V}_{O_2} + (1-k)\dot{V}_{O_2} \tag{1b}$$

The rate of oxygen supply in the inferior (IVC) and susperior vena cava (SVC) is given by Eqs. 2 and 3, respectively:

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

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

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:

$$Q_P = Q_{SVC} + Q_{shunt} \tag{4}$$

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

$$\begin{aligned} &C_{SVC,O_2}Q_{SVC} + C_{shunt,O_2}Q_{shunt} + \dot{V}_{O_2,L} \\ &= C_{PV,O_2}Q_P \end{aligned} \tag{4b}$$

The combined cardiac output can be expressed as

$$CO = Q_{IVC} + Q_{SVC} \tag{5}$$

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

$$\dot{V}_{O_2,L} = \dot{V}_{O_2} \tag{6}$$

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

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

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

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

In the derivation, use has been made of Eq. (6). Since (rearranging Eq. 5) $Q_{SVC} + Q_{shunt} = CO - Q_{IVC} + Q_{shunt}$, from Eq. (7) we can write the following expression, useful to derive the oxygen delivery to the arterial system:

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

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

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

This expression for $\left(C_{a,O_2} - C_{PV,O_2}\right)Q_{IVC}$ can be substituted at the right-hand side of Eq. (8), to give the result

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

and finally

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

where the position $x \equiv \left(Q_{SVC}+Q_{shunt}\right)/Q_{IVC}$ has been made.

Eq. (10) is a generalization of the formula provided by (Santamore et al. 1998) for the case of a BCPA without additional source of pulmonary flow. Of course, the two formulas coincide for $Q_{shunt} = 0$.

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 β, the fraction of the CO which is driven into the systemic-to-pulmonary shunt. From Eq. 10, the value of systemic oxygen delivery ($C_{a,O_2} \times CO$) can be immediately derived. Furthermore, with some additional derivations, the value of oxygen saturation, both globally and regionally (in the lower and upper circulation) can be calculated, similarly to the approach in (Santamore et al., 1998).

3 RESULTS

The results of the simulation indicate that there is an overall improvement in blood oxygen saturation level, either globally or at the regional (IVC or SVC) level, as a function of the parameter β.

It must be underlined that 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 (Salim et al., 1995).

In particular, Fig. 2 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. Such values can be considered relevant especially for exercise conditions, when the lower body requires a higher oxygen increase than the upper body.

Also for the regional blood oxygen saturation level the presence of additional blood flow is beneficial. Fig. 3 shows how the IVC oxygen saturation varies as a function of Q_{IVC}/Q_{SVC} and β; similarly for the SVC oxygen saturation in Fig. 4. A marked improvement is observed, especially for the minimum physiological value of Q_{IVC}/Q_{SVC} in Fig. 3, allowing the oxygen saturation in the lower circulation to reach over 70% (for β=0.3), from 60% in absence of additional pulmonary flow.

A lesser effect, albeit clearly positive, is given by the presence of the shunt in the oxygen saturation in the upper circulation (Fig. 4).

It should be considered that, in the study, the flow through the shunt was not calculated in the total CO, which was instead calculated as the sum of the caval flows, Q_{IVC}+ Q_{SVC}. Thus, for increasing values of β the work exerted by the heart is higher, at the same CO level, since it must provide also the flow in the shunt. This should be clearly considered together with the advantages in terms of blood oxygenation, during surgery planning.

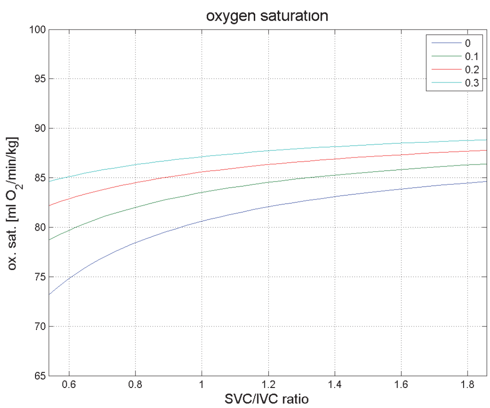

Figure 2: Oxygen saturation vs. SVC/IVC ratio, as a function of the parameter β, which characterizes the systemic-to-pulmonary shunt.

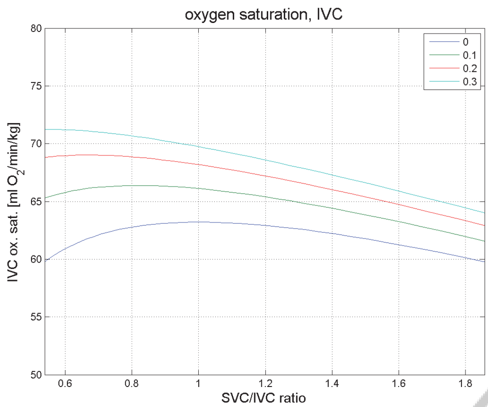

Figure 3: IVC oxygen saturation vs. SVC/IVC ratio.

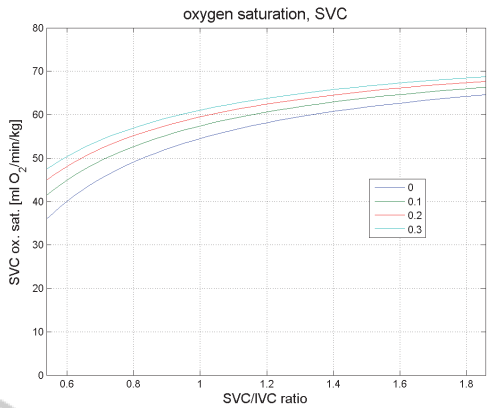

Figure 4: SVC oxygen saturation vs. SVC/IVC ratio.

In the model, we did not take explicitly into account the contribution of the lungs' vascular bed to the observed effects. Actually such a role impacts on the pulmonary resistance, and therefore on Q_P, so that it is implicitly considered. Nevertheless, a more accurate description of the pulmonary circulation could improve the predictive capabilities of the model, given the importance of lung physiology and development in univentricular patients.

4 CONCLUSIONS

The mathematical modelling of the circulation after BCPA and an additional source of pulmonary blood flow, such as the modified Blalock-Taussig shunt, demonstrated clear advantages of this surgical option, with respect to the simple BCPA, in terms of systemic blood oxygen saturation, especially in the lower circulation. The results are substantially in accordance with recent reports (van Slooten et al., 2012) of a retrospective study with a remarkable sample size (82 patients), which confirmed the advantage of additional pulmonary blood flow in BCPA patients.

In the future, we intend to apply this mathematical model, with the necessary modifications, 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 (Giannico et al., 2006). We look forward to evaluating the predictive capabilities of this model by comparing the results with actual clinical data: this step will indicate whether further refinements of the model are necessary.

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