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*Original Article*

# The functionally univentricular circulation in the Norwood procedure: from analysis of fluid dynamics to surgical procedures

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THE NORWOOD PROCEDURE AND ITS modifications have become the most commonly used surgical procedures for patients with hypoplastic left heart syndrome. Many efforts have been made to understand the fluid dynamics of the Norwood circulation, with the major impetus coming from the lumped-parameter model described by Migliavacca et al.[1] In this model, a large number of variables have been analysed to understand their effect on the Norwood circulation. In the clinical setting, some of these parameters can be influenced by the surgeon during the operation. The shunt has been demonstrated to be the critical element in regulating the pulmonary and systemic flows, with the goal of the surgeon being to obtain balanced flows. In order to do this, it is possible to influence the flow through the shunt in three ways:

- by augmenting the pressure of perfusion of the shunt, with a suboptimal aortic reconstruction that can leave some residual pressure gradient. This can work like an increment of systemic vascular resistance;
- by varying the size of the shunt;
- by varying the type of architecture of the shunt, since flow through the shunt is dependent on the site of anastomosis, the angle with the vessels, and so on.

In order to validate or verify the results obtained from the lumped-parameter model, we have reviewed our experience with the Norwood procedure since 1992.

## Materials and methods

Since 1992, we have performed 45 operations, 25 in males and 20 in females, the patients having a mean weight at operation of 3 ± 0.4 kilograms, with a range from 1.9 to 3.9 kilograms, and a mean age of 8.4 ± 7.1 days, with a range from 2 to 43 days.

Of the patients, 39 had hypoplastic left heart syndrome, while the remaining 6 presented with its variants having aortic atresia. The mean period of extracorporeal circulation time was 241 ± 77 minutes, with a range from 146 to 470 minutes, the mean time of cross-clamping was 53 ± 38 minutes, with a range from 0 to 153 minutes, and the mean period of cardio-circulatory arrest was 38 ± 35 minutes, with a range from 0 to 118 minutes. Since 1999, we have routinely avoided cardio-circulatory arrest with selective cerebral perfusion. The mean stay in the intensive care unit was 9.6 ± 6.9 days, and the mean period of ventilation was 7.5 ± 5.4 days. In all, 14 patients (31%) left the operating room with a closed sternotomy. Among the remaining 31, the sternotomy was subsequently closed in 22 (49%), while 9 patients (20%) died with an open sternum.

## Results

Fifteen patients died in hospital (33.3%), with an additional 8 patients (17.8%) dying whilst waiting for the second stage Norwood procedure, at a mean

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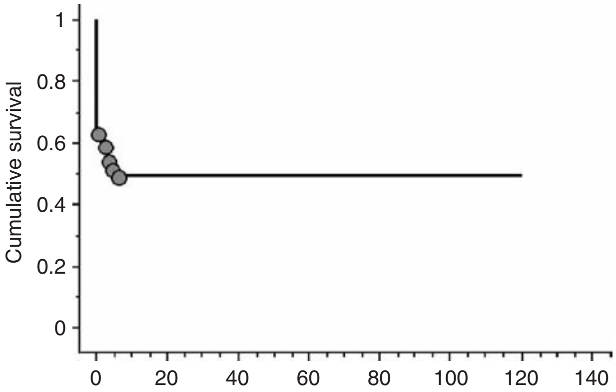

**Figure 1.**
*Cumulative survival curve according to Kaplan–Meier.*

interval of 3 months after the first stage. The cumulative survival curve according to Kaplan–Meier shows that there is no late mortality among patients who underwent a bi-directional cavopulmonary anastomosis, or a total cavopulmonary connection (Fig. 1). The analysis of our mortality shows a significant reduction since 1999. Of the last 12 cases, we lost only 1 patient (8.3%), with a statistically significant reduction in mortality compared to the loss of 42.4% of the 33 patients undergoing surgery before 1999 ($p = 0.03$). We have critically analysed our experience to understand if the technical changes adopted over this period were responsible for this marked improvement.

### *Aortic reconstruction*

During our experience, we used three techniques for aortic reconstruction. At the beginning, we used a simple pericardial patch, but this had the problem of wrinkling. It is impossible to obtain a three-dimensional reconstruction from a bi-dimensional patch, and this can result in an irregular aortic profile and turbulent flow. This alteration of flow is very important in causing aortic recoarctation. For these reasons, we switched to a preformed pericardial patch that can be tailored to fit the size of the patient. In this way, we were able to obtain a regular profile of the reconstructed aorta (Fig. 2).[2] This technique also made it possible to avoid turbulent flow, and to obtain a low rate of recoarctation. The patch is made of two layers of heterologous pericardium, and is modelled according to the size of the patient. The inner profile is sutured with a double running 7/0 of Prolene, reinforcing the suture with hystoacrylic glue. The patch is constructed during the cooling phase, with no increase in the operative time. It is then used to reconstruct the aorta. We obtain a very physiological aortic profile. The third method we used is direct anastomosis.[3] This has reduced the time needed for anastomosis, and should help in producing less turbulent flow through a widely patent aorta. The rate of recoarctation is quite low, and we have never encountered problems with left pulmonary arterial stenosis.

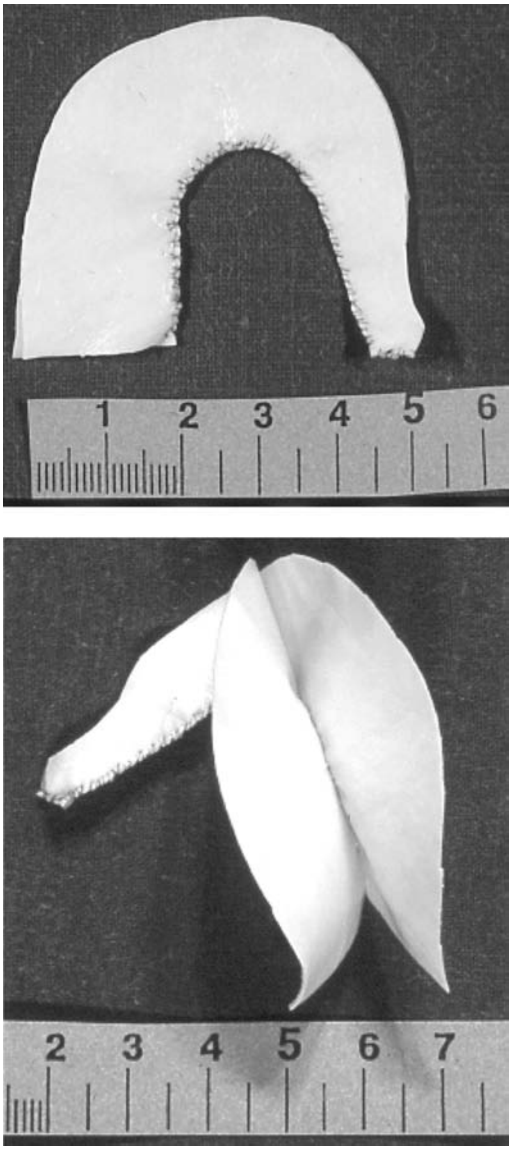

**Figure 2.**
*The preformed pericardial patch tailored according to the described technique.*

Having divided our experience in three periods according to the technique used for aortic reconstruction, we have assessed if the different techniques were significant in lowering our mortality (Fig. 3). In the first period, from 1992 to 1995, 18 patients received an aortic reconstruction with pericardial patches, simple or preformed according to the technique proposed by our group, with a hospital mortality of 38.8%. In the second period, from 1996 to 1998, 15 patients were treated using the direct anastomosis without heterologous material, but the mortality did not differ significantly in these

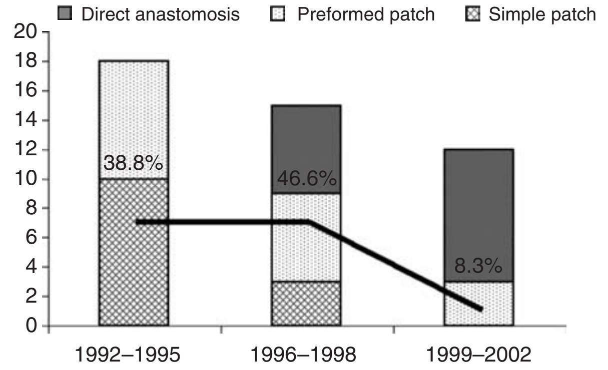

**Figure 3.**
*Temporal distribution of the technique used for aortic reconstruction relative to mortality.*

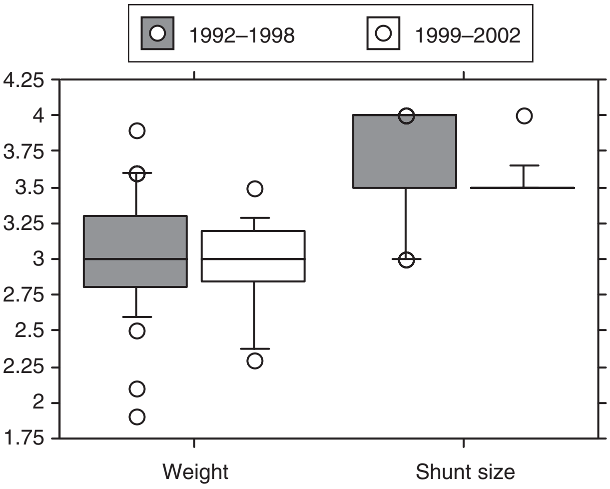

**Figure 4.**
*Distribution of the weight and shunt size in the two periods.*

periods. In the last 12 patients, undergoing surgert between 1999 and 2002, we used only direct anastomosis or a preformed patch, and the mortality was significantly lower (8.3%, p = 0.03).

### *Size of the shunt*

During our experience, we have progressively reduced the size of the shunt. Analysing the distribution of the size of the shunt in the period from 1992 to 1998, compared to 1999 to 2002, and assuming that there is no difference in weight of the patients, we used larger shunts in the first period, while in the second period, except for 1 patient, we used only 3.5-millimetre shunts (Fig. 4). In 8 patients, we downsized the shunt using a metallic clip placed during the stay on the intensive care unit, with 7 downsizings performed during the first time frame, confirming our tendency to use oversized shunts.

### *Architecture of the shunt*

We used three patterns of anastomosis throughout our experience. At the beginning, we made a direct anastomosis between the posterior aspect of the reconstructed aorta and the pulmonary tunnel, but this was difficult to construct, difficult to manage at reintervention, and difficult to calibrate. We then adopted the modified Blalock–Taussig shunt. This was much easier to construct and to recalibrate, but produced, in our experience, preferential flow to the right pulmonary artery, leading potentially to underdevelopment of the left pulmonary artery. For this reason, in our last patients we have anastomosed the shunt on the pulmonary bifurcation. This technique retains the advantages of the modified Blalock–Taussig shunt, but gives the opportunity to leave pulsatile accessory flow to the pulmonary arteries. Using this technique, we also noticed a more balanced development of the pulmonary arteries. The hospital mortality using these techniques, however, did not differ significantly.

### *Extra-corporeal circulation*

When analysing our technique for the extra-corporeal circulation, we have noticed a progressive lowering of the time required for this phase, probably due not only to the increased surgical experience, but also to the great number of direct aortic anastomosis performed during the last period. We have not used circulatory arrest since 1999, when we routinely adopted selective cerebral perfusion. This is performed through a needle in the brachiocephalic trunk, or with a little cannula ending with a bulb positioned inside the snared artery. In the last three cases, we first constructed the proximal anastomosis of the 3.5-millimetre polytetrafluoroethylene shunt, and then we cannulated it to perfuse the brain as described by Pigula et al.[4] When we analysed the influence of selective cerebral perfusion, we found a significantly lower mortality among the patients treated with this technique (p = 0.02). Among these patients, we also noted a significantly lower incidence of delayed sternal closure (p = 0.01), showing that avoidance of circulatory arrest has repercussions not only on cerebral, but also on systemic circulation.

From this analysis, we have assembled our own optimal surgical strategy. This involves selective cerebral perfusion, aortic reconstruction either with a preformed pericardial patch or with direct anastomosis, optimal sizing of the shunt with central anastomosis, early clipping of the shunt in case of low cardiac output, and early use of nitric oxide or carbon dioxide in the intensive care unit to modify the pulmonary and systemic vascular resistances. With this optimal surgical strategy, we have performed 19 Norwood operations and lost only 2 patients (10.5%), significantly lower than in our experience with the initial 26 patients.

## Conclusions

Retrospective analysis of our results shows that clinical experience has matched the conclusions of the computational model of the Norwood circulation. Indeed, all the techniques used throughout our experience have undergone continuous critical review due to the analysis of the results obtained. This evolution has lead to the same results obtained by the bioengineers, with the object of reducing the rate of recoarctation, reducing the size of the shunt, and obtaining perfect geometry for the shunt. We also believe that the technique used for perfusion also plays an important role in the success of the Norwood procedure, and our data seem to confirm this notion. Considering the Norwood operation as the result of the surgical, anaesthesiological and perfusional techniques, nonetheless, there are still some variables that cannot be reproduced with a mathematical model.

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