Norwood Reconstruction Using Continuous
Coronary Perfusion: A Safe and Translatable
Technique

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Background. Continuous coronary perfusion during Norwood reconstruction offers the theoretic advantage of less postoperative cardiac dysfunction. The avoidance of a cardiac and circulatory arrest period allows time for a more deliberate aortic reconstruction while the heart remains beating. This single-center study was designed to compare patient results using this method vs standard cardiac arrest for Norwood reconstruction.

Methods. A retrospective review was done of 32 patients undergoing Norwood reconstruction from November 2004 to July 2011. The operations in the most recent 16 consecutive patients were performed under deep hypothermia with constant coronary and cerebral perfusion. Continuous coronary perfusion was provided by a cannula inserted into the proximal aorta. The operations in the prior 16 consecutive patients were performed using deep hypothermia, selective cerebral perfusion, and cardioplegic arrest during aortic reconstruction.

Results. Survival in the beating-heart group was 87.5% (14 of 16) vs 62.5% (10 of 16) in the standard group (p = 0.22). No patients in the beating-heart group required extracorporeal membrane oxygenation vs 3 in the standard group. Postoperative cardiac function was similar for both groups. The beating-heart cohort had lower peak lactate levels (8.2 mEq/L) than the standard group (10.7 mEq/L, p = 0.022).

Conclusions. This study presents the largest series of Norwood operations in which the entire aorta is augmented while delivering continuous coronary perfusion. The technique is applicable to any size aorta and represents a safe alternative because outcomes for survival, freedom from extracorporeal membrane oxygenation, postoperative cardiac function, and lactate levels were all noninferior compared with the standard technique.

Staged surgical palliation is the mainstay of treatment for hypoplastic left heart syndrome and its variants [1, 2]. Stage I of the palliation, or the Norwood procedure, consists of an atrial septectomy to provide adequate intracardiac mixing, patent ductus arteriosus ligation, neoaorta reconstruction consisting of a Damus-Kaye-Stansel anastomosis with homograft augmentation of the aortic arch, and a shunting procedure to provide pulmonary blood flow. Aside from the atrial septectomy, the Norwood reconstruction is largely an extracardiac operation. As such, the possibility exists to perform the entire neonatal operation without the need for cardioplegic cardiac arrest. In fact, various iterations of beating-heart Norwood operations have been described [3–5]. In light of previous evidence from our institution that neonatal hearts are more vulnerable to ischemia and reperfusion than mature hearts, a beating-heart approach to Norwood reconstruction may have the potential to benefit postoperative myocardial function [6].

Beginning in March 2007, a concerted effort was made at our institution to minimize cardioplegic cardiac arrest time during stage I palliation. Initially, coronary perfusion and cerebral perfusion were supplied concomitantly by a graft sewn to the innominate artery with a clamp on the proximal arch as the aortic arch reconstruction was performed. The proximal neoaortic repair was then done with a short period of cardiac arrest. This technique eventually evolved into our current approach, which obviates the need for cardioplegic cardiac arrest.

We hypothesized that a strategy using continuous coronary perfusion for Norwood reconstruction could be equally safe and effective as traditional Norwood repair. This report compares patient outcomes at our institution with this “beating-heart,” or continuous coronary perfusion approach, and the standard Norwood repair

Accepted for publication March 18, 2013.


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Published by Elsevier Inc

http://dx.doi.org/10.1016/j.athoracsur.2013.03.049

0003-4975/536.00
involving cardioplegic cardiac arrest for the entire neo-aortic reconstruction.

Material and Methods
This study was approved by the University of Iowa Institutional Review Board. The need for individual patient consent was waived.

Patient Population
We retrospectively reviewed the records of all neonates undergoing Norwood reconstruction at our institution from November 2004 until July 2011. The last 16 consecutive Norwood operations performed in this group were done with the beating-heart technique. During a transition period before the development of our beating-heart approach, a short, partial cardiac arrest period was used for the most proximal aspects of the neo-aortic reconstruction in 6 patients (50% survival). The analysis excluded these patients because these operations were performed with a distinctly different technique than the comparison groups. Thus, the comparison, or “standard Norwood” group in this study precedes these patients and consists of the 16 most-recent patients undergoing cardiac arrest for the entire neo-aortic reconstruction.

Operative Techniques
All patients undergoing a standard Norwood operation in this study were maintained with continuous antegrade cerebral perfusion through a 3.5- or 4-mm shunt sewn onto the innominate artery and connected to the arterial inflow of the cardiopulmonary bypass circuit. Patients were cooled to a core (rectal) temperature of 18° to 20°C. Once the desired core temperature was reached, the heart was arrested with cold-blood cardioplegia, and selective cerebral perfusion was commenced. The atrial septectomy and complete neo-aortic reconstruction were performed under cardiac arrest. Coronary perfusion was resumed for the completion of the pulmonary arterial shunt.

The beating-heart Norwood operations were performed with similar arterial cannulation and cooling strategies. The difference lies in aortic reconstruction, which is performed in a sequential fashion. A clamp (Yasargil clip) is placed across the aortic arch between the innominate and left common carotid arteries. This begins selective cerebral and coronary perfusion with flows of 20 to 40 mL/kg/min, depending on the head saturations measured by near-infrared spectroscopy.

Clamps are then placed on the descending aorta, left subclavian, and left common carotid arteries. This allows exclusion of the aortic arch. Reconstruction can then begin with removal of ductal tissue and opening of the arch to start the reconstruction. Figure 1A depicts this arrangement. The patch is sewn to the level of the clamp between the innominate and left common carotid arteries. A clamp is then placed on the origin of the innominate artery, while the clamp between the innominate and left common carotid arteries is removed.

The aortotomy is continued from the arch down the ascending aorta to the level of the planned pulmonary arterial amalgamation. An accessory arterial perfusion line is used to provide continuous coronary flow using
a cardioplegia spike (Fig 1B) or an olive-tip cannula (Fig 1C) secured in the proximal ascending aorta. Larger aortas can accommodate the cardioplegia spike with a clamp above, whereas smaller aortas require the olive-tip cannula to be placed in the lumen and secured with a vessel loop tourniquet. We successfully used the olive-tip technique in aortas as small as 1.5 mm in this study.

Coronary perfusion is assessed qualitatively throughout the operation by observing the beating heart, pink epicardium, and appropriate ventricular distention. The aortic reconstruction continues proximally, and the pulmonary arterial anastomosis is completed in the classic Damus-Kaye-Stansel fashion, with coronary and cerebral perfusion maintained throughout. The innominate artery clamp is removed and air removal is performed. The descending aorta clamp is removed, followed by the left common carotid artery clamp. The patient is rewarmed while the distal end of the pulmonary artery shunt is completed.

Data Collection
A database was constructed for all Norwood patients from November 2004 until July 2011, including preoperative, operative, and postoperative data. Variables collected consisted of age, weight, sex, cardiac diagnosis, cardiac arrest time, cardiopulmonary bypass time, type of pulmonary artery shunt, serial lactate levels, postoperative echocardiographic function, requirement for postoperative extracorporeal membrane oxygenation (ECMO), and survival. Cardiac diagnoses included hypoplastic left heart syndrome, double-inlet left ventricle, hypoplastic aortic arch with a ventricular septal defect, and tricuspid atresia with transposition of the great arteries. The peak postoperative lactate level was recorded. Normalization of lactate levels was measured in hours and determined by the first postoperative value measured below the upper limit of the normal reference range by our laboratory (2.2 mEq/L). For all patients in this study, preoperative and immediate postoperative echocardiograms in each patient were operated on using a continuous coronary perfusion technique for the entire stage I operation. Importantly, all operations included an amalgamation at the level of the proximal ascending aorta and proximal main pulmonary artery. Patient demographics, diagnoses, and operative variables are reported in Table 1. By nature of the operative technique, cardiac arrest time was significantly different between the two groups. No other preoperative or operative variables measured showed any significant differences between the two operative approaches.

Postoperative Variables and Outcomes
Postoperative variables and outcomes are summarized in Table 2. The global response to the operation was assessed indirectly by recording peak lactate levels and the time to normalization of lactate levels in the postoperative period. The mean peak lactate level was only 8.2 mEq/L for the beating-heart cohort compared with 10.7 mEq/L for the standard Norwood group \( p = 0.022 \). However, the median time to resolution of lactic acidosis (lactate < 2.2 mEq/L) demonstrated no difference between the two groups.

Myocardial function was queried by reviewing preoperative and postoperative echocardiograms in each patient. There was at least a mild decrease in function.

Table 1. Patient and Operative Characteristics

<table>
<thead>
<tr>
<th>Variable</th>
<th>Beating-Heart (n = 16)</th>
<th>Standard (n = 16)</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demographics</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age, d</td>
<td>7 (4–23)</td>
<td>6 (2–59)</td>
<td>0.49</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>3.26 ± 0.57</td>
<td>3.18 ± 0.55</td>
<td>0.73</td>
</tr>
<tr>
<td>Male sex</td>
<td>14 (87.5)</td>
<td>11 (68.8)</td>
<td>0.39</td>
</tr>
<tr>
<td>Diagnosis</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HLHS</td>
<td>15 (93.8)</td>
<td>13 (81.3)</td>
<td></td>
</tr>
<tr>
<td>DILV</td>
<td>0</td>
<td>2 (12.5)</td>
<td></td>
</tr>
<tr>
<td>Hypoplastic arch/VSD</td>
<td>1 (6.3)</td>
<td>0 (0)</td>
<td></td>
</tr>
<tr>
<td>Tricuspid atresia/TGA</td>
<td>0 (0)</td>
<td>1 (6.3)</td>
<td></td>
</tr>
<tr>
<td>Operation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cardiac arrest time, min</td>
<td>0</td>
<td>74 (34–128)</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>CPB time, min</td>
<td>187 (142–303)</td>
<td>190 (147–310)</td>
<td>0.53</td>
</tr>
<tr>
<td>Sano shunt</td>
<td>15 (93.8)</td>
<td>14 (87.5)</td>
<td>0.89</td>
</tr>
</tbody>
</table>

*Continuous variables are displayed as median (range) or mean ± standard deviation as appropriate; categoric variables are presented as frequency (percentage). Statistical significance \( p < 0.05 \). CPB = cardiopulmonary bypass; DILV = double-inlet left ventricle; HLHS = hypoplastic left heart syndrome; TGA = transposition of the great arteries; VSD = ventricular septal defect.
postoperatively in 4 patients (25%) in the beating-heart group vs 6 patients (37.5%) undergoing standard Norwood repair ($p = 0.31$).

From an outcomes standpoint, there was a shift towards less postoperative ECMO (0% in the beating-heart vs 18.8% in the standard Norwood, $p = 0.23$) and improved survival (87.5% in the beating-heart vs 62.5% in the standard Norwood, $p = 0.22$) with the beating-heart strategy, although these changes did not reach statistical significance.

**Comment**

We retrospectively compared postoperative variables and outcomes between two operative approaches to stage I Norwood reconstruction. One approach used standard cardioplegic cardiac arrest for the entire neoaortic reconstruction, whereas the other was performed with a beating heart for all parts of the operation. Our findings demonstrate that we are able to perform the operation without a cardiac arrest period and that peak lactate levels are lower in the postoperative period for those patients undergoing the beating-heart procedure. There was also a trend toward better postoperative cardiac function, less ECMO, and improved survival with this approach.

Theoretically, the avoidance of a cardiac arrest period would seem to be advantageous during cardiac operations. As a result, many beating-heart procedures have been developed in adult and pediatric cardiac surgery in the last few decades [7]. However, evidence from animal models suggests that the neonatal heart may be even more sensitive to ischemia and reperfusion than mature hearts [6]. Although this concern may be balanced by some evidence that the neonatal heart serves as an environment more amenable to repair, it may be advantageous nonetheless to apply these beating-heart concepts to neonatal cardiac operations.

Patients with hypoplastic left heart syndrome and its variants represent the logical application of this approach. By the nature of the Norwood reconstruction being mostly an extracardiac operation, the possibility exists to perform all steps involved while maintaining continuous coronary perfusion. In addition, it would reason that preservation of myocardial function from ischemia and reperfusion injury would be even more vital in the univentricular heart.

The concept of minimizing the cardiac arrest period during Norwood arch repair has been presented by a number of groups [8, 9]. An abbreviated cardiac arrest period was still performed in these patients for augmentation of the ascending aorta. Kishimoto and colleagues [3] were the first to detail an entire Norwood operation performed with a beating heart. Later, with a minor modification, this work was reproduced [4]. In both reports, however, no augmentation of the aorta was performed proximal to the origin of the innominate artery.

Photiadis and associates [5] presented a study comparing 13 standard Norwood reconstructions with 13 beating-heart repairs. Included in the beating-heart cohort were 7 patients in whom continuous coronary perfusion was described as being delivered by a cardioplegia spike and involving ascending aortic augmentation. The study we have outlined here represents the largest series of Norwood operations in which the entire aorta is augmented while delivering continuous coronary perfusion. The introduction of the olive-tip cannula as an alternative to the cardioplegia spike in providing coronary perfusion allows this strategy to be applicable to any size aorta.

The conduct of the beating-heart operation lends itself to several advantages. First, continuous coronary perfusion can be visually assessed throughout the operation by observing the heart as pink and beating. Perfusion can then be titrated using these visual cues. Second, the technique described is applicable to any size aorta. The cardioplegia spike used for larger aortas can be placed before opening the proximal aorta and provides uninterrupted coronary perfusion. The olive-tip cannula for smaller aortas requires a brief period of opening the ascending aorta and inserting the tip into the ascending aortic lumen before initiating coronary perfusion. However, this tip is quite mobile, and visualization of the proximal aorta-to-pulmonary arterial amalgamation remains quite satisfactory. In addition, the olive-tip provides assurance of patency in patients with small aortas, because the bulbous tip is only removed immediately before tying the final stitch of the neoaortic anastomosis.

Third, we take advantage of the lack of a cardiac arrest period to devote additional attention to the neoaortic reconstruction. Specifically, we sew a double-suture line for the entire reconstruction to aid in hemostasis.

The final but likely the most beneficial aspect of the beating-heart technique is the freedom from the time constraints inherent in periods of cardiac and circulatory arrest. As a result, the beating-heart strategy enables a measured approach to Norwood reconstruction. Although any strategy resulting in protracted periods of cardiopulmonary bypass should be viewed with caution.

### Table 2. Postoperative Variables and Outcomes

<table>
<thead>
<tr>
<th>Variable</th>
<th>Beating-Heart (n = 16)</th>
<th>Standard (n = 16)</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laboratory variables</td>
<td></td>
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</tr>
<tr>
<td>Peak lactate level, mEq/L</td>
<td>8.2 ± 2.58</td>
<td>10.7 ± 3.43</td>
<td>0.02b</td>
</tr>
<tr>
<td>Lactate normalization time, h</td>
<td>20 (8–30)</td>
<td>16.5 (4–53)</td>
<td>0.98</td>
</tr>
<tr>
<td>Echo function—no decrease</td>
<td>12 (75%)</td>
<td>10 (71.4)</td>
<td>0.31</td>
</tr>
<tr>
<td>Postoperative ECMO</td>
<td>0</td>
<td>3 (18.8)</td>
<td>0.23</td>
</tr>
<tr>
<td>Survival</td>
<td>14 (87.5)</td>
<td>10 (62.5)</td>
<td>0.22</td>
</tr>
</tbody>
</table>

a Continuous variables are displayed as median (range) or mean ± standard deviation as appropriate; categoric variables are presented as frequency (percentage). b Statistically significant ($p < 0.05$). ECMO = extracorporeal membrane oxygenation.
in light of associations with increased rates of morbidity and mortality, this particular technique achieves quite favorable outcomes. Such an approach could alleviate much of the reluctance in training congenital heart surgery fellows and junior faculty in this procedure and greatly aid in their overall operative development.

This study has some limitations. Neonates undergoing continuous coronary perfusion without cardioplegic cardioplegic cardiac arrest were compared with neonates undergoing standard Norwood reconstruction with cardioplegic cardiac arrest during a study period of 7 years. The standard Norwood patients constitute the earlier cases in this study group, whereas the beating-heart Norwood patients represent the last 16 patients during this interval. Thus, unmeasured confounders related to historical controls, patient selection, and postoperative management may influence the comparison of outcomes over the course of the study period. The investigation also suffers from the common limitations inherent in retrospective reviews. Finally, although this represents the largest comparison of a beating-heart technique with the standard Norwood reconstruction, the study is prone to type II error and is likely underpowered to detect small differences in outcomes between the groups.

In conclusion, the Norwood reconstruction can be performed safely using continuous coronary perfusion techniques and the avoidance of cardioplegic cardiac arrest. Outcomes for survival, freedom from ECMO, postoperative cardiac function, and lactate levels were all noninferior for the beating-heart strategy, with survival approaching the results of even the best Norwood series.

More important, this method allows a measured approach to Norwood reconstruction, free from the time restrictions of cardiac and circulatory arrest. Such an approach could offer a translatable alternative in the operative development of congenital fellows and junior faculty.

References


DISCUSSION

DR PETROS V. ANAGNOSTOPOULOS (Madison, WI): Joe, two questions. The first question is how do you do the septectomy? Do you have inotrope scores in the postoperative period or diastolic pressures in the pre-Glenn catheter? I understand that it makes sense to minimize ischemia, but your technique is technically a little bit more difficult. And the question is, can you show any advantages that justify the extra work?

DR TUREK: I am sorry, I didn’t hear the first question. How do I do . . . ?

DR ANAGNOSTOPOULOS: The atrial septectomy.

DR TUREK: Sucker bypass was used for the atrial septectomy. As far as the inotropes, I didn’t have complete access to the inotropes for the patients who were done in the standard Norwood procedure, so I really don’t know how they compare. I can just tell you anecdotally that from the information I did have, there really appeared to be no difference.

DR EMILE A. BACHA (New York, NY): Joe, very nice presentation; nice work. Two questions: Do you know of any laboratory data that compare myocardial oxygen consumption at 18° in the beating empty heart vs the arrested heart? Which one is better? We know the empty beating heart consumes much less oxygen, but then the arrested heart in diastole might be consuming even less oxygen. So again, I don’t know at 18° whether it is better to have a heart beating empty and perfused continuously, or arrested with a good cardioplegic solution. Are there any laboratory data on that?

DR TUREK: Yes, that is a great question. There are no laboratory data that I know of on that topic. We had considered doing this technique without hypothermia. But from a safety margin standpoint, we just decided that it is probably best to cool in case something were to happen during the procedure.

DR BACHA: So I have used this technique, and intuitively I have just stayed at 28° or higher when I was perfusing the heart continuously. The other quick question is, we know from the work on technical performance scores that the impact of technical excellence at the end of the operation, that is, lack of coarctation and the presence of perfect coronary perfusion, is really what determines, to a large extent, the outcome of these babies as opposed to whether you perfuse the heart continuously or not. So my question to you, between the two groups, were there any differences in terms of technical performance scores, such as arch obstruction or coronary perfusion postoperatively and so forth? And what I am getting too is can you visualize the structures well enough to do what you need to do?

DR TUREK: I can tell you the visualization is actually excellent. I haven’t had any problem with visualization. Where you would worry, I guess, would be the proximal amalgamation for
visualization; however, it is actually very good. And the other thing about that is you actually are testing the patency of your aorta because you have to get that olive-tipped cannula out at the end of the operation anyway.

DR RICHARD N. GATES (Orange, CA): Yes, just one question. What was your myocardial protection strategy in the standard group?

DR TUREK: In particular what are you looking for?

DR GATES: Well, did you do all blood cardioplegia, intermittent?

DR TUREK: I’m sorry, what kind of cardioplegia we used?

DR GATES: Yes. What did you do for the standard group to protect the heart?

DR TUREK: We used cold-blood cardioplegia for all 16 of the standard patients and the same when we had our transition period, when we were doing some partial periods of cardiac arrest. Then, obviously, no cardioplegia was used for the beating heart cohort.

DR GATES: All right. Thanks.

DR ANDRÉ RÜFFER (Erlangen, Germany): To give a possible answer to Professor Bacha’s question: we have performed an animal laboratory study in small piglets, weighing between 10 and 12 kg, where we compared aortic arch surgery on the beating heart to crystalloid cardioplegia. We found out that at 1 and 2 hours after coming off from bypass, there was no significant difference regarding levels of troponin and myoglobin. Furthermore, there was no difference in apoptosis. On the other hand, we have very good clinical results with beating-heart surgery; however, there seems to be a kind of subendocardial ischemia even in the continuously perfused and empty beating heart.