Bilateral pulmonary artery banding in higher risk neonates with hypoplastic left heart syndrome

Harold M. Burkhart, MD,[a] Yuki Nakamura, MD,[a] Anas Salkini, MD,[b] Randall M. Schwartz, MD,[c] Courtney D. Ranallo, MD,[d] Elizabeth S. Makil, MD,[b] Matthew Campbell, MD,[b] Suanne M. Daves, MD,[c] Emilie D. Henry, MD,[d] and Arshid Mir, MD[b]

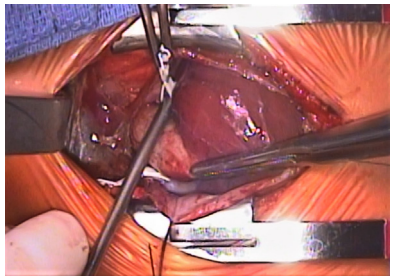
ABSTRACT

Objectives: Limited data on performing bilateral pulmonary artery banding (BPAB) before stage 1 Norwood procedure suggest that some patients may benefit through the postponement of the major cardiopulmonary bypass procedure. The objective of this study was to evaluate the effectiveness of BPAB in the surgical management of high-risk patients with hypoplastic left heart syndrome (HLHS).

Methods: A retrospective review of all high-risk neonates with HLHS who underwent BPAB at our institution was performed. No patients, including those with intact or highly restrictive atrial septum (IAS), were excluded.

Results: Between October 2015 and April 2021, 49 neonates with HLHS (including 6 with IAS) underwent BPAB, 40 of whom progressed to the Norwood procedure. Risk factors for not progressing to the Norwood procedure after BPAP include low birth weight ($P = .043$), the presence of multiple extracardiac anomalies ($P = .005$), and the presence of genetic disorders ($P = .028$). Operative mortality was 7.5% (3/40). IAS was associated with operative mortality ($P = .022$).

Conclusions: The strategy of BPAB prestage 1 Norwood procedure was successful in identifying at-risk patients and improving Norwood survival. Although not all patients will need this hybrid approach, a significant number can be expected to benefit from this tactic. These results support the need for a substantial hybrid strategy, in addition to a primary stage 1 Norwood surgical strategy, in the management of HLHS. (JTCVS Open 2023;16:689-97)



Intraoperative photo showing left pulmonary artery being banded over a 2.5-mm probe.

CENTRAL MESSAGE

High-risk neonates may benefit from staging with bilateral pulmonary artery banding before Norwood.

PERSPECTIVE

High-risk neonates with hypoplastic left heart syndrome have substantial operative risk undergoing Norwood operation. Staging greater-risk patients with a BPAB before the Norwood procedure may improve survival by making them better candidates for the major cardiac procedure.

The successful surgical management of hypoplastic left heart syndrome (HLHS) remains a challenge to cardiac surgeons and multidisciplinary care teams, with stage 1 Norwood mortality ranging from 7% to 39%.[1,2] Multiple innovations including the right ventricle-to-pulmonary artery (RV-PA) shunt, aortic arch reconstruction techniques, as well as the hybrid palliative approach have been developed, all aimed at improving HLHS outcomes.[3-5] Recently, Ota and colleagues[6] reported on their rapid-staged bilateral pulmonary artery banding (BPAB) approach before Norwood palliation.

The idea of avoiding cardiopulmonary bypass and a complex cardiac operation in the early neonatal period while giving time for stabilization and the declaration of issues not initially apparent at birth (necrotizing enterocolitis, infection, genetic and extracardiac anomalies) suggested a staged Norwood procedure, using BPAB, may be an appropriate strategy for high-risk neonates with HLHS. We hypothesized that the staged Norwood approach for patients deemed at greater risk for primary Norwood would be a viable strategy.

From the [a]Division of Cardiovascular and Thoracic Surgery, [b]Section of Pediatric Cardiology, [c]Department of Anesthesia, and [d]Section of Pediatric Critical Care, University of Oklahoma Health Sciences Center, Oklahoma City, Okla.

Received for publication April 17, 2023; revisions received July 7, 2023; accepted for publication Aug 2, 2023; available ahead of print Sept 2, 2023.

Address for reprints: Harold M. Burkhart, MD, Division of Cardiovascular and Thoracic Surgery, University of Oklahoma Health Sciences Center, P.O. Box 26901, WP-2230, Oklahoma City, OK 73105 (E-mail: Harold-burkhart@ouhsc.edu).

2666-2736

https://doi.org/10.1016/j.xjon.2023.08.005

Abbreviations and Acronyms

BCPS = bidirectional cavopulmonary shunt
BPAB = bilateral pulmonary artery banding
CI = confidence interval
DOL = day of life
ECMO = extracorporeal membrane oxygenation
HLHS = hypoplastic left heart syndrome
IAS = intact or severely restrictive atrial septum
IQR = interquartile range
LBW = low birth weight
PA = pulmonary artery
RV-PA = right ventricle-to-pulmonary artery

METHODS

Design and Study Population

This study was approved by the institutional review board of the University of Oklahoma Health Sciences Center (institutional review board 11708, February 20, 2020) with a waiver of consent. The medical records were reviewed retrospectively. Between October 2015 and April 2021, 49 patients with risk factors for the primary Norwood procedure underwent BPAB. Both HLHS and its variants were included. No high-risk patient was excluded. During this same time period, 11 patients without risk factors underwent primary Norwood procedure. All 11 survived the procedure and are not included in this study. All patients were kept on prostaglandin E1 to maintain ductal patency. No patient underwent ductal stenting. The second-stage Norwood plus bidirectional cavopulmonary shunt (BCPS) strategy (comprehensive stage 2) was not adopted. Note that no patients were offered comfort care during the study period, including 6 patients with HLHS and intact atrial septum or severely restrictive atrial septum (IAS).

The risk factors for the primary Norwood procedure, which existed before undergoing BPAB, were established in our program through our previous experience and literature review. They included prematurity, low birth weight (LBW), multiple extracardiac anomalies, genetic disorders, heterotaxy syndrome, moderate or greater atrioventricular valve regurgitation, tiny ascending aorta (2 mm or smaller), moderately or severely depressed cardiac function, coronary artery fistulas, IAS, restrictive atrial septum, atresia of the coronary artery ostium, and pre-BPAB morbidity (mechanical ventilation, sepsis, shock, necrotizing enterocolitis, and neurologic issues). Prematurity was defined as a child birth less than 37 gestational weeks of age. LBW was defined as less than 2500 g. Genetic disorders were defined as those with a known genetic syndrome or genetic lesions detected by chromosomal microarray analysis and believed to be highly pathogenic by a genetic consultation. All the patients except 1 patient with IAS underwent a chromosome analysis using fluorescence in situ hybridization and chromosomal microarray analysis. Patients with IAS were those who needed interventions for the atrial septum immediately after birth. Restrictive atrial septum was defined as either IAS or the need for a balloon atrial septostomy before BPAB. Shock was defined as hypotension, hyperlactatemia, and metabolic acidosis with pH <7.2. Incidence of the risk factors in the 49 patients are shown in Table 1. Pre-BPAB patient demographics of the patients are shown in Table 2.

Operative mortality was per the Society of Thoracic Surgeons Congenital Heart Surgery Database and included all deaths occurring during the same hospitalization in which the operation was performed, even if after 30 days, and deaths occurring after discharge from the hospital within 30 days of the operation.

The primary outcome was outcomes toward subsequent operations in the 49 patients under our staged Norwood strategy. The secondary outcome was the need of intervention on banded pulmonary arteries (PAs) up to the time of BCPS with our staged Norwood strategy.

Bilateral Pulmonary Artery Banding

BPAB was performed through a median sternotomy using a 0.4-mm-thick expanded polytetrafluoroethylene strip (GORE-TEX Cardiovascular Patch; W.L. Gore & Associates, Inc) clipped over a 2.5-mm probe (Figure 1). Epicardial or transesophageal echocardiography was performed in the operating room to confirm appropriate banding. We typically aimed for a relatively tight banding to reduce the chances of pulmonary overcirculation, providing a more stable postoperative period. The inner diameters of the banded pulmonary arteries measured by the echocardiography were typically 1.8 to 2.0 mm. Postoperatively, supplemental oxygen was used as needed. Ductal patency was maintained through the use of a prostaglandin E_1 infusion.

Seven patients underwent concomitant atrial septectomy. Our approach to HLHS/IAS has been surgical atrial septectomy and BPAB immediately after birth. At our institution, we provide childbirth-related services in the same building as the children's hospital. After cesarean delivery, these patients were emergently taken to our operating room. Two dedicated pediatric cardiac anesthesiologists rapidly secured the airway and obtained arterial and central venous access. Following a limited transthoracic echocardiogram to confirm the diagnosis, atrial septectomy under ventricular fibrillation using cardiopulmonary bypass was performed. Looser banding than the usual was applied in this setting because of elevated pulmonary vascular resistance. After initial placement of BPAP over a 3-mm probe, we tightened the band, aiming for an echocardiography measurement of 2.2 to 2.4 mm. Delayed sternal closure was routinely applied, and the BPABs were tightened further if necessary. Six patients were managed with this approach. Another patient with a mean pressure gradient of 11 mm Hg through a small interatrial communication underwent atrial septectomy and BPAB on day of life (DOL) 5 after a failed catheter-based septal intervention.

Management During the Period Between BPAB and the Norwood Procedure

After BPAB, the patients were managed in our pediatric cardiac intensive care unit with the aims of extubation and establishing enteral feeding. The presence of significant noncardiac abnormalities discovered postoperatively excluded the patient from the Norwood procedure. Further, from a cardiac standpoint, in patients with significant tricuspid valve regurgitation after BPAB, a heart transplantation was offered as an option. Coronary artery fistulae, even significant ones, were not a contraindication to the Norwood procedure. In patients who were born premature or with LBW, we waited until they reached a corrected term gestational age or a body weight close to 3 kg before proceeding with the Norwood procedure. In patients with poor pulmonary status due to prematurity, infection, or HLHS/IAS, the Norwood procedure was postponed until the lung condition improved.

The Norwood Procedure

The Norwood procedure was performed under deep hypothermia with antegrade cerebral perfusion. The aortic arch was reconstructed using a pulmonary homograft patch. A RV-PA conduit was used for pulmonary blood flow in all but 2 patients with a HLHS variant requiring a modified Blalock Taussig shunt. The RV-PA conduit was placed to the right of the neoaorta with the proximal dunk technique using a thin-walled ringed expanded polytetrafluoroethylene graft (GORE-TEX Vascular Graft; W.L. Gore & Associates, Inc). For the banded branch PAs, the previous bands were removed and surrounding scar tissue was excised. Typically, if the bands had been in place for less than 2 weeks, vascular dilators were used to successfully dilate the band site. Intraoperative ballooning of the PAs under direct visualization was performed using a catheter with a balloon diameter of 4 mm when the interval between BPAB and

TABLE 1. Incidence of the risk factors in the 49 patients

Prematurity, n (%)	9 (18.4)
Low birth weight, n (%)	13 (26.5)
Multiple extracardiac anomalies, n (%)	3 (6.1)
Genetic disorders, n (%)	8 (16.3)
Heterotaxy syndrome, n (%)	1 (2)
Moderate or greater TR, n (%)	5 (10.2)
Moderately or severely depressed cardiac function	0 (0.0)
Tiny ascending aorta (≤2 mm), n (%)	17 (34.7)
Coronary artery fistulas, n (%)	8 (16.3)
IAS, n (%)	6 (12.2)
Restrictive atrial septum, n (%)	17 (34.7)
Atresia of the coronary artery ostium, n (%)	1 (2)
Pre-BPAB mechanical intubation, n (%)	36 (73.5)
Pre-BPAB shock, n (%)	4 (8.2)
Pre-BPAB shock with MOF, n (%)	1 (2)

TR, Tricuspid regurgitation; *IAS*, intact atrial septum or severely restrictive atrial septum; *BPAB*, bilateral pulmonary artery banding; *MOF*, multiple organ failure.

the Norwood procedure was longer than 2 weeks. Delayed sternal closure was routinely applied.

Statistical Analysis

Normally distributed continuous variables were expressed as mean and standard deviation, and were analyzed using either Student *t* test or Welch *t* test as appropriate. Variables with a non-normal distribution were expressed as median and interquartile range (IQR) and were analyzed using Mann–Whitney *U* test. Categorical variables were expressed as frequencies (n) and percentages (%), and were analyzed using the Fisher exact test. In the patients who underwent a Norwood procedure, an overall transplant-free survival was calculated using Kaplan–Meier survival analysis with 95% equal precision confidence bands. The starting time was taken as days of the Norwood procedure. Statistical analysis was performed using SAS 9.4 (SAS Institute).

TABLE 2. Pre-BPAB patient demographics

Variable	
Sex, n (%)	
Male	34 (69.4)
Female	15 (30.6)
Weight at birth, kg, mean ± SD	2.9 ± 0.5
Age at BPAB, d, median (IQR)	6.0 (4.0)
Weight at BPAB, kg, mean ± SD	3 ± 0.5
Anatomy, n (%)	
MS/AS	16 (32.7)
MS/AA	11 (22.5)
MA/AA	10 (22.4)
MA/AS	4 (8.2)
HLHS variant	8 (16.3)
TR, n (%)	
None/trivial	29 (59.2)
Mild	15 (30.6)
Moderate	5 (10.2)
Severe	0 (0.0)
Ascending aorta size, mm, mean ± SD	2.8 ± 2.5
Pre-BPAB balloon septostomy, n (%)	11 (22.5)

SD, Standard deviation; *BPAB*, bilateral pulmonary artery banding; *IQR*, interquartile range; *MS*, mitral stenosis; *AS*, aortic stenosis; *AA*, aortic atresia; *MA*, mitral atresia; *HLHS*, hypoplastic left heart syndrome; *TR*, tricuspid regurgitation.

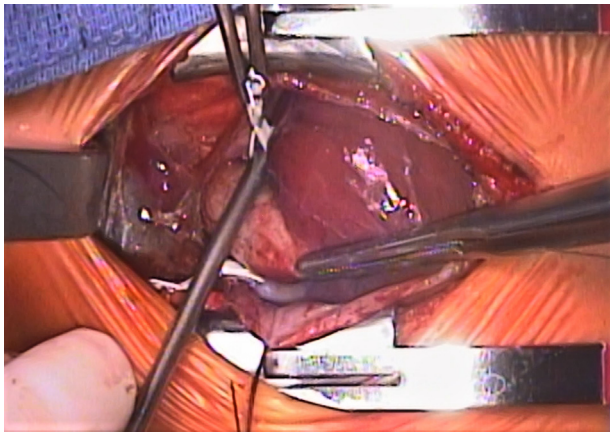


FIGURE 1. Intraoperative photo showing left pulmonary artery being banded over a 2.5-mm probe.

RESULTS

Reaching the Norwood Procedure after BPAB

Among the 49 patients with the risk factors, 40 patients (81.6%) progressed to the Norwood procedure. Table 3 describes the risk factors in the 49 patients dichotomized into those who reached the Norwood procedure and those who did not. Regarding genetic disorders, only 1 patient with Turner syndrome was diagnosed before BPAB. Seven additional patients were diagnosed as having a genetic syndrome after BPAB. Risk factors for failing to advance to the Norwood procedure include LBW ($P = .043$), the presence of multiple extracardiac anomalies ($P = .005$), and the presence of genetic disorders ($P = .028$).

Nine patients did not advance to Norwood procedure. One patient had progressive tricuspid and mitral regurgitation after BPAB and underwent a successful heart transplantation. Two patients with HLHS/IAS who underwent surgical atrial septostomy and BPAB at birth passed away due to multiorgan failure secondary to cardiac failure and sepsis. Post-BPAB extracorporeal membrane oxygenation (ECMO) support was required in 3 patients, all of whom did not survive to Norwood. One patient with a birth weight of 2.1 kg required ECMO support after 2 weeks of stability post-BPAB due to poor cardiac output secondary to restriction of the patent ductus arteriosus. The patent ductus arteriosus was stented and ECMO support was successfully discontinued. However, progressive stenosis of the stent and continued poor cardiac function led to the patient's demise. Another patient had cardiac

TABLE 3. Risk factors in the 49 patients and progression to the Norwood procedure

Variable	Norwood (n = 40)	Non-Norwood (n = 9)	*P* value
Prematurity, n (%)	9 (22.5)	0 (0.0)	.179
Low birth weight, n (%)	8 (21.620.0)	5 (55.6)	.043
Multiple extracardiac anomalies, n (%)	0 (0.0)	3 (33.3)	.005
Genetic disorders, n (%)	4 (10.0)	4 (44.4)	.028
Heterotaxy syndrome, n (%)	0 (0.0)	1 (11.1)	.184
Moderate or greater TR, n (%)	5 (12.5)	0 (0.0)	.569
Tiny ascending aorta (≤2 mm), n (%)	15 (37.5)	2 (22.2)	.467
Coronary artery fistulas, n (%)	8 (20.0)	0 (0.0)	.322
IAS, n (%)	4 (10.0)	2 (22.2)	.302
Restrictive atrial septum, n (%)	14 (35.0)	3 (33.3)	>.999
Atresia of the coronary artery ostium, n (%)	1 (2.5)	0 (0.0)	>.999
Pre-BPAB mechanical intubation, n (%)	29 (72.5)	7 (77.8)	>.999
Pre-BPAB shock, n (%)	3 (7.5)	1 (11.1)	.569
Pre-BPAB shock with MOF, n (%)	0 (0.0)	1 (11.1)	.184

TR, Tricuspid regurgitation; *IAS*, intact atrial septum or severely restrictive atrial septum; *BPAB*, bilateral pulmonary artery banding; *MOF*, multiple organ failure.

arrest several hours after BPAB, and ECMO support was initiated. Despite successful discontinuation of ECMO support, the patient passed away from multiple gastrointestinal perforations. The patient was diagnosed as having 16p11.2 deletion syndrome postmortem. The other patient with pre-BPAB mechanical intubation needed ECMO support from left atrial rupture during an attempted catheter-based balloon atrial septostomy 3 days after BPAB and never recovered. The final 3 patients had multiple extracardiac anomalies and highly pathogenic genetic lesions leading to the parental decision to transition to comfort care.

Early Results After the Norwood Procedure

Overall, 40 patients underwent the Norwood procedure at median DOL 24.5 (IQR, 18.5) with a median body weight of 3.5 (IQR, 0.7) kg. The cardiopulmonary bypass and aortic crossclamp times were 142.6 ± 20.3 and 48.7 ± 9.7 minutes, respectively. Intraoperative ballooning of the PAs was performed in 26 patients (65.0%) with older ages at the Norwood operation (median DOL, 32.5; IQR, 19.0 vs median 14.0; IQR, 8.0, $P < .001$), reflecting our strategy. Operative mortality was 7.5% (3/40). Table 4 describes the relationship between the risk factors and the hospital mortality. The first mortality was a patient with

TABLE 4. Risk factors and hospital mortality after the Norwood procedure

Variable	Survival (n = 37)	Mortality (n = 3)	*P* value
Prematurity, n (%)	8 (21.6)	1 (33.3)	.545
Low birth weight, n (%)	7 (18.9)	1 (33.3)	.498
Multiple extracardiac anomalies, n (%)	0 (0.0)	0 (0.0)	N/A
Genetic disorders, n (%)	4 (10.8)	0 (0.0)	>.999
Heterotaxy syndrome, n (%)	0 (0.0)	0 (0.0)	N/A
Moderate or greater TR, n (%)	5 (13.5)	0 (0.0)	>.999
Tiny ascending aorta (≤2 mm), n (%)	14 (37.8)	1 (33.3)	>.999
Coronary artery fistulas, n (%)	8 (21.6)	0 (0.0)	>.999
IAS, n (%)	2 (5.4)	2 (66.7)	.022
Restrictive atrial septum, n (%)	12 (32.4)	2 (66.7)	.276
Atresia of the coronary artery ostium, n (%)	1 (2.7)	0 (0.0)	>.999
Pre-BPAB mechanical intubation, n (%)	27 (73.0)	2 (66.7)	>.999
Pre-BPAB shock, n (%)	3 (8.1)	0 (0.0)	>.999
Pre-BPAB shock with MOF, n (%)	0 (0.0)	0 (0.0)	N/A

N/A, Not available; *TR*, tricuspid regurgitation; *IAS*, intact atrial septum or severely restrictive atrial septum; *BPAB*, bilateral pulmonary artery banding; *MOF*, multiple organ failure.

prematurity and LBW who suffered a right coronary artery thrombus on postoperative day one. This patient required ECMO and passed away after surgery to remove the clot. This was the only patient that required ECMO (2.5%) postoperatively. The second mortality was in a patient with HLHS/IAS who had progressive pulmonary vein stenosis and arch obstruction 3 months after the Norwood operation and passed away after another surgery to revise these lesions. The last patient, also with HLHS/IAS, underwent a BCPS during the same hospitalization as the Norwood procedure. Takedown of BCPS was required one month after the BCPS due to pulmonary infection resulting in death 12 days later.

Subsequent Patients' Status After the Norwood Procedure

Subsequent patients' statuses after the Norwood procedure in the 40 patients are shown in Figure E1. Of the 38 patients excluding 1 patient with Norwood 30-day mortality and another patient with Norwood hospital mortality who did not reach a BCPS, 31 patients survived to a BCPS and 1 patient reached a biventricular repair after the Norwood procedure. (32/38, 84.2%). Table E1 shows the relationship of the risk factors and the failure to reach a BCPS. The failure to reach a BCPS was defined as either an interstage death (n = 2) or a delay in BCPS (waiting for more than 6 months after the Norwood procedure, n = 4). Of the 2 patients with an interstage death, 1 patient had poor cardiac function and was waiting for a heart transplantation. For the other patient with a cardiac arrest at home, the cause was unknown. BCPS has been delayed in four patients due to poor lung conditions, all of whom had prematurity ($P = .012$).

Overall Transplant-Free Survival

Figure 2 shows the overall survival curve for all 49 patients undergoing BPAP. Kaplan–Meier-estimated transplant-free survival was 75.3% (95% confidence interval [CI], 51.1-88.7) and 65.5% (95% CI, 40.6-82.0) at 1 and 2 years, respectively. Figure 3 shows the overall survival curve for the 40 patients who underwent the Norwood procedure, with the time zero being the day of the Norwood procedure. Kaplan–Meier estimated transplant-free survival was 87.0% (95% CI, 71.4-94.4) and 77.8% (95% CI, 60.2-88.3) at 1 and 2 years, respectively.

Pulmonary Artery Intervention After the Staged Norwood Procedure

Among the overall 40 patients who underwent the staged Norwood procedure, interstage catheter interventions on the PAs were performed in 14 patients of 39 patients (35.9%) who had cardiac catheterizations after the Norwood procedure. This was not associated with the need for intraoperative ballooning of the PAs during the Norwood procedure (11/26 among patients with PA ballooning during the Norwood procedure vs 3/13 without PA ballooning, $P = .304$). Surgical interventions on the PAs during BCPS were performed in 22.6% (7/31), which were not associated with the need for intraoperative ballooning of the PAs during the Norwood procedure (5/21 among patients with PA ballooning during the Norwood procedure vs 2/8 among the others, $P > .999$).

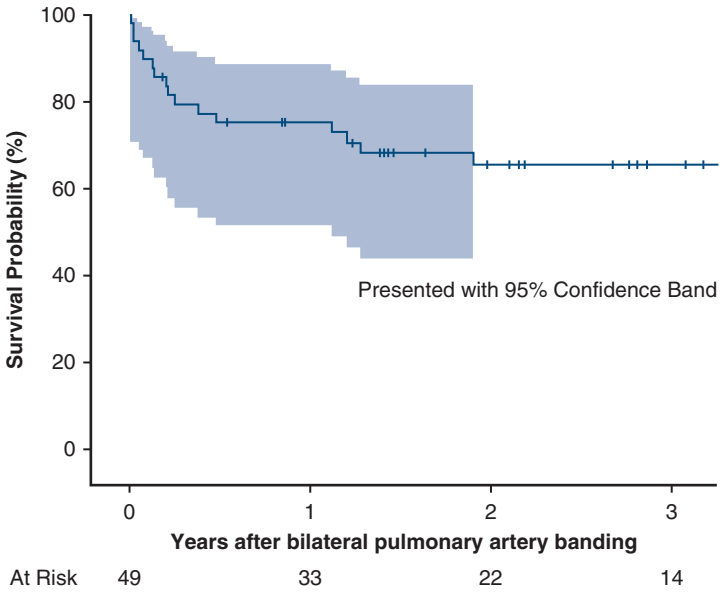


FIGURE 2. Bilateral pulmonary artery banding in greater-risk neonates with HLHS. Bilateral pulmonary artery banding was performed in 49 neonates with HLHS. In total, 40 patients progressed to Norwood procedure with a 30-day mortality of 2.5%. Risk factors for failure to advance to Norwood include LBW, extracardiac anomaly and genetic anomaly.

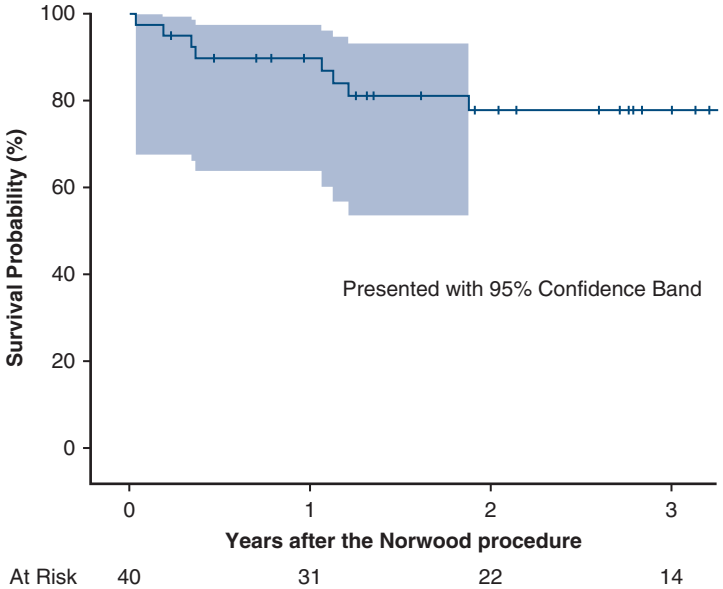


FIGURE 3. Overall transplant-free survival. Overall transplant-free survival curve for the 40 patients with the risk factors undergoing Norwood procedure is shown.

DISCUSSION

In an effort to improve the outcomes of patients with HLHS in our renewed comprehensive congenital surgical program, we instituted a policy of BPAB in greater-risk patients before the Norwood procedure. We hypothesized that this approach would allow time for establishment of a stable, balanced circulation, the identification of undiscovered risk factors, and offer the advantage of performing the more complex cardiac reconstruction on a more mature neonate.

In our 49 high-risk patients with HLHS or its variants who underwent BPAB under the staged Norwood approach, 40 patients reached the Norwood procedure. LBW, multiple extracardiac anomalies, and genetic disorders affected survival or candidacy for the Norwood procedure, whereas prematurity or IAS did not (Figure 3). Of 8 patients with genetic disorders, the diagnoses were made after BPAB in 7. In 3 of the 7 patients, the diagnosis of highly pathogenic genetic lesions or a genetic syndrome resulted in their guardian's decision to withdraw care. Operative mortality for the Norwood procedure was 7.5%, including 1 patient who reached BCPS during the same hospitalization as the Norwood operation. IAS was related to the hospital operative mortality whereas prematurity, LBW, or genetic disorders were not. During the Norwood procedure, intraoperative ballooning of the PAs was performed when the interval between BPAB and the Norwood procedure was longer than 2 weeks. This did not correlate to the need for interstage catheter interventions or surgical interventions during BCPS on the PAs. The failure to reach a BCPS was influenced only by prematurity. In our staged Norwood approach, BPAB functioned to screen extremely high-risk patients such as those with multiple extracardiac anomalies or highly pathogenic genetic disorders, and to mitigate sequelae cause by prematurity or LBW toward the Norwood procedure. This led to the low hospital operative mortality after the Norwood procedure even though we included patients with IAS. However, prematurity still influenced interstage results after the successful Norwood procedure. Some risk factors for the primary Norwood procedure established in our program, such as tiny ascending aorta or restrictive atrial septum, seemed to be insignificant during a pathway toward a BCPS.

Staged Norwood in HLHS

Others have reported using this strategy for HLHS or high-risk single-ventricle patients. Ota and colleagues[6] reported BPAB in 14 patients before stage 1 Norwood with the thought that this would lessen risk factors and beneficially postpone the major bypass operation beyond the newborn period. Patients obtaining Norwood procedure after BPAP had lower lactates and improved urine output versus patients receiving primary Norwood procedure. They reported excellent results in this small group, with no early deaths and one late death. This strategy has not been limited to HLHS, with others reporting success with various single-ventricle anomalies.[7]

Ceneri and colleagues[8] recently reported their experience using a hybrid strategy for high-risk neonates with HLHS or variants. Their overall survival was 70% after a median of 9 months following the hybrid procedure. They concluded that the hybrid strategy could be used successfully as a bridge to either a delayed Norwood or a comprehensive stage II operation in high-risk neonates.

There are numerous advantages to this approach. The obvious one is that time is given to identify and mitigate risk factors. In addition to allowing for growth in LBW or early gestational age newborns, time is given to identify issues such as genetic or extracardiac anomalies. Certainly, in our experience, the discovery of genetic disorders has influenced the parental decision to withdraw care. Besides avoiding a major cardiopulmonary bypass reconstructive operation, one has to acknowledge that these risk factors could have influenced the surgical outcome of a primary stage 1 Norwood. Other comorbidities, such as infection, valve insufficiency, arrythmia, or concern for necrotizing enterocolitis, are given time for adequate treatment before stage 1 Norwood with this strategy. We believe these infants have a stable pulmonary to systemic flow ratio after BPAB, which helps with lung recovery and improved systemic perfusion, allowing for a period of somatic growth, since feeds are tolerated with improved gut perfusion. Furthermore, patients having undergone BPAB are more stable at the time of stage 1 Norwood, with our anesthesia colleagues reporting a more stable intraoperative course to initiating cardiopulmonary bypass compared with patients without BPAB. Similar to previous reports, the low postoperative lactate levels in our BPAB Norwood patients support this strategy in a group that excluded no patients. Finally, it has been suggested that avoiding cardiopulmonary bypass and possibly deep hypothermic arrest in neonates with LBW or lower gestational age may have benefits in neurodevelopment in the long term.[9,10]

There are some disadvantages to this approach. First, this approach requires a second operation, which may prolong the hospital stay. Second, there is concern that manipulation of the PAs will result in the need for more surgical/catheter-based PA interventions. Our data show that the need for PA intervention did not correlate with intraoperative PA ballooning at the time of stage 1 Norwood with our PA intervention rate being comparable to others.[1] This is likely due to the rapid 2-stage strategy to Norwood. A recent study did show increased risk for PA intervention in patients with band placement for greater than 90 days.[11]

Risk Factors of BPAB

The presence of extracardiac anomalies, genetic disorders, or LBW was each associated with not proceeding on to stage 1 Norwood. This is not surprising, as all are known risk factors for the stage 1 Norwood procedure. Tabbutt and colleagues[12] reported LBW and genetic abnormality as independent risk factors for 30-day and hospital mortality in a 15-center study of 549 patients undergoing Norwood procedure. In a single-institution study of 111 patients with HLHS undergoing Norwood, Stasik and colleagues[13] reported LBW and noncardiac anomalies to be independent risk factors of hospital mortality. Similarly, Ono and colleagues[14] demonstrated LBW and extracardiac anomalies being risk factors for mortality in their single-center experience of 322 neonates undergoing the Norwood procedure. Finally, Alsoufi and colleagues[15] showed that among patients who had undergone single-ventricle palliation, the risk of hospital mortality was twice (24% vs 12%) in patients with genetic syndromes and extracardiac anomalies. These risk factors, at the very least, need to be considered when deciding on proceeding with BPAB much less stage 1 Norwood procedure.

Intact Atrial Septum

When looking at the high-risk patients who survived to undergo stage 1 Norwood, the only significant risk factor for survival was the presence of an intact atrial septum. This is not unexpected, as it is a known risk factor for stage 1 Norwood.[16,17] A recent large multicenter study assessing all fetuses with HLHS/IAS showed that overall discharge survival was 39%, even in patients who had undergone previous successful fetal intervention to decompress the left atrium.[18] Indeed, many institutions do not offer surgical palliation in the presence of IAS. We have a standard approach to these patients consisting of immediately transferring the newborn to the operating room for emergency BPAB and surgical atrial septectomy. We have found this to be advantageous over a catheter-based septostomy in that we avoid time delays, the potential for inadequate septectomy or wire/balloon complications. Overall, in our cohort, of 6 patients with HLHS/IAS, 3 survived stage 1 Norwood procedure. This survival is similar to the report by Sood and colleagues in which they used a combined approach consisting of surgical PAB and interventional septostomy and ductal stent.[19]

Study Limitations

Limitations include the single-center, retrospective nature of this report with a limited number of patients and institutional bias with respect to critical care, interventional and surgical management.

CONCLUSIONS

The strategy of using BPAB pre-stage 1 Norwood procedure was satisfactory for high-risk patients undergoing the Norwood. We found that LBW, the presence of multiple extracardiac anomalies, and the presence of genetic disorders were all risk factors for not moving forward with stage 1 Norwood procedure after BPAB. In addition, we noted excellent stage 1 Norwood procedure survival in patients transitioning via staged Norwood. Although not all patients will need this hybrid approach, a significant number can be expected to benefit from this tactic. These results support the need for a substantial hybrid strategy, in addition to a primary stage 1 Norwood surgical strategy, in all successful, comprehensive congenital cardiac surgical programs.

Conflict of Interest Statement

The authors reported no conflicts of interest.

The *Journal* policy requires editors and reviewers to disclose conflicts of interest and to decline handling or reviewing manuscripts for which they may have a conflict of interest. The editors and reviewers of this article have no conflicts of interest.

We thank all our nurses and clinical staff in the Oklahoma Children's Hospital cardiac intensive care unit for their commitment to and excellent care provided for our patients and their families.

References

1. Ohye RG, Sleeper LA, Mahony L, Newburger JW, Pearson GD, Lu M, et al. Comparison of shunt types in the Norwood procedure for single-ventricle lesions. *N Engl J Med*. 2010;362:1980-92.
2. Ohye RG, Schranz D, D'Udekem Y. Current therapy for hypoplastic left heart syndrome and related single ventricle lesions. *Circulation*. 2016;134:1265-79.
3. Sano S, Ishino K, Kado H, Shiokawa Y, Sakamoto K, Yokota M, et al. Outcome of right ventricle-to-pulmonary artery shunt in first-stage palliation of hypoplastic left heart syndrome: a multi-institutional study. *Ann Thorac Surg*. 2004;78:1951-8.
4. Burkhart HM, Ashburn DA, Konstantinov IE, De Oliveira NC, De Oliviera NC, Benson L, et al. Interdigitating arch reconstruction eliminates recurrent coarctation after the Norwood procedure. *J Thorac Cardiovasc Surg*. 2005;130:61-5.
5. Galantowicz M, Cheatham JP, Phillips A, Cua CL, Hoffman TM, Hill SL, et al. Hybrid approach for hypoplastic left heart syndrome: intermediate results after the learning curve. *Ann Thorac Surg*. 2008;85:2063-70; discussion 2070-1.
6. Ota N, Murata M, Tosaka Y, Ide Y, Tachi M, Ito H, et al. Is routine rapid-staged bilateral pulmonary artery banding before stage 1 Norwood a viable strategy? *J Thorac Cardiovasc Surg*. 2014;148:1519-25.
7. Guleserian KJ, Barker GM, Sharma MS, Macaluso J, Huang R, Nugent AW, et al. Bilateral pulmonary artery banding for resuscitation in high-risk, single-ventricle neonates and infants: a single-center experience. *J Thorac Cardiovasc Surg*. 2013;145:206-13; discussion 213-4.
8. Ceneri NM, Desai MH, Tongut A, Ozturk M, Ramakrishnan K, Staffa SJ, et al; Children's National Hospital Hybrid Working Group. Hybrid strategy in neonates with ductal-dependent systemic circulation and multiple risk factors [Erratum in: *J Thorac Cardiovasc Surg*. 2023;165:408.]. *J Thorac Cardiovasc Surg*. 2022;164:1291-303.e6. https://doi.org/10.1016/j.jtcvs.2021.11.103
9. Licht DJ, Shera DM, Clancy RR, Wernovsky G, Montenegro LM, Nicolson SC, et al. Brain maturation is delayed in infants with complex congenital heart defects. *J Thorac Cardiovasc Surg*. 2009;137:529-36.
10. Hirsch JC, Jacobs ML, Andropoulos D, Austin EH, Jacobs JP, Licht DJ, et al. Protecting the infant brain during cardiac surgery: a systematic review. *Ann Thorac Surg*. 2012;94:1365-73.
11. Davies RR, Radtke WA, Klenk D, Pizarro C. Bilateral pulmonary arterial banding results in an increased need for subsequent pulmonary artery interventions. *J Thorac Cardiovasc Surg*. 2014;147:706-12.
12. Tabbutt S, Ghanayem N, Ravishankar C, Sleeper LA, Cooper DS, Frank DU, et al. Risk factors for hospital morbidity and mortality after the Norwood procedure: a report from the Pediatric Heart Network Single Ventricle Reconstruction Trial. *J Thorac Cardiovasc Surg*. 2012;144:882-95.
13. Stasik CN, Gelehrter S, Goldberg CS, Bove EL, Devaney EJ, Ohye RG. Current outcomes and risk factors for the Norwood procedure. *J Thorac Cardiovasc Surg*. 2006;131:412-7.
14. Ono M, Kido T, Wallner M, Burri M, Lemmer J, Ewert P, et al. Comparison of shunt types in the neonatal Norwood procedure for single ventricle. *Eur J Cardiothorac Surg*. 2021;60:1084-91.
15. Alsoufi B, McCracken C, Oster M, Shashidharan S, Kanter K. Genetic and extracardiac anomalies are associated with inferior single ventricle palliation outcomes. *Ann Thorac Surg*. 2018;106:1204-12.
16. Vida VL, Bacha EA, Larrazabal A, Gauvreau K, Thiagaragan R, Fynn-Thompson F, et al. Hypoplastic left heart syndrome with intact or highly restrictive atrial septum: surgical experience from a single center. *Ann Thorac Surg*. 2007;84:581-6.
17. Tanem J, Rudd N, Rauscher J, Scott A, Frommelt MA, Hill GD. Survival after Norwood procedure in high-risk patients. *Ann Thorac Surg*. 2020;109:828-33.
18. Jantzen DW, Moon-Grady AJ, Morris SA, Armstrong AK, Berg C, Dangel J, et al. Hypoplastic left heart syndrome with intact or restrictive atrial septum: a report from the International Fetal Cardiac Intervention Registry. *Circulation*. 2017;136:1346-9.
19. Sood V, Zampi J, Romano JC. Hypoplastic left heart syndrome with an intact atrial septum. *JTCVS Open*. 2020;1:51-6.

Key Words: hypoplastic left heart syndrome, bilateral pulmonary artery bands, Norwood, congenital cardiac surgery, single-ventricle palliation

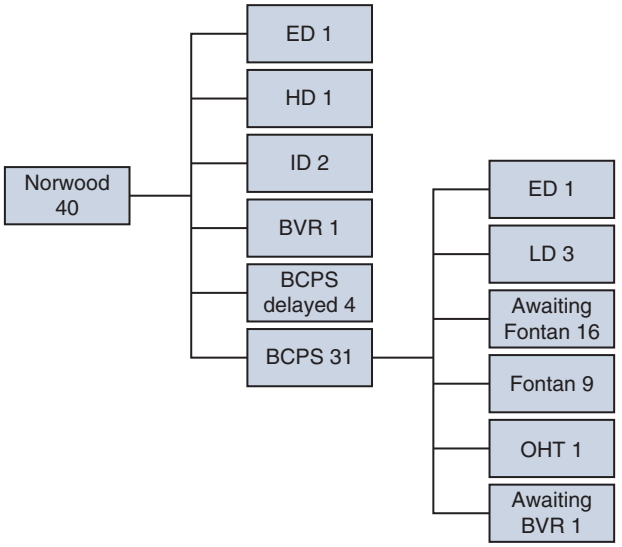


FIGURE E1. Follow-up after the Norwood procedure in 40 patients with the risk factors. Patients' status subsequent to the Norwood procedure in 40 patients with the risk factors is shown. The patient with ED after a BCPS was the one who underwent a BCPS during the same hospitalization as the Norwood procedure. *ED*, death at 30 days; *HD*, hospital death after 30 days; *ID*, interstage death; *BVR*, biventricular repair completion; *LD*, late death; *BCPS*, bidirectional cavopulmonary shunt; *OHT*, orthotopic heart transplantation.

TABLE E1. Risk factors and the failure to reach a BCPS in the Norwood survivors

Variable	Success (n = 32)	Failure (n = 6)	*P* value
Prematurity, n (%)	4 (12.5)	4 (66.7)	.012
Low birth weight, n (%)	4 (12.5)	3 (50.0)	.063
Multiple extracardiac anomalies, n (%)	0 (0.0)	0 (0.0)	N/A
Genetic disorders, n (%)	4 (12.5)	0 (0.0)	>.999
Heterotaxy syndrome, n (%)	0 (0.0)	0 (0.0)	N/A
Moderate or greater TR, n (%)	5 (15.6)	0 (0.0)	.570
Tiny ascending aorta (≤2 mm), n (%)	12 (37.5)	2 (33.3)	>.999
Coronary artery fistulas, n (%)	6 (18.7)	2 (33.3)	.587
IAS, n (%)	3 (9.4)	0 (0.0)	>.999
Restrictive atrial septum, n (%)	11 (34.4)	2 (33.3)	>.999
Atresia of the coronary artery ostium, n (%)	1 (3.1)	0 (0.0)	>.999
Pre-BPAB mechanical intubation, n (%)	23 (71.9)	5 (83.3)	>.999
Pre-BPAB shock, n (%)	3 (9.4)	0 (0.0)	>.999
Pre-BPAB shock with MOF, n (%)	0 (0.0)	0 (0.0)	N/A

N/A, Not available; *TR*, tricuspid regurgitation; *IAS*, intact atrial septum or severely restrictive atrial septum; *BPAB*, bilateral pulmonary artery banding; *MOF*, multiple organ failure.