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The Short-Term Outcomes of the Rapid Two Stage Norwood Strategy at a Single Center

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Abstract

Background: The conventional Norwood operation for hypoplastic left heart syndrome is typically performed within first week of life, during the transitional circulatory period. Long-term survival remains suboptimal, with complications such as cardiac arrest, necrotizing enterocolitis, acute kidney injury and stroke, driving mortality and morbidity. To mitigate these risks, we implemented a rapid two-stage Norwood: bilateral pulmonary artery banding (PAB) at 0 - 3 days with PGE_1 for ductal patency, followed by delayed Norwood at 3 - 4 weeks of age. This approach aims to stabilize the transitional circulation while allowing time for end-organ maturation before the Norwood. We report our single-center short-term outcomes. **Methods:** Single-center retrospective study. **Results:** Thirteen patients underwent the rapid two-stage Norwood. There was no mortality after PAB; two (15.4%) died after Norwood. Median gestational age was $38^{5/7}$ weeks; median age and weight at PAB were 2 days and 3.13 kg. Three underwent atrial septostomy, and 3 needed PGE_1 escalation for ductal constriction. All patients tolerated some enteral feeds pre-Norwood, and renal mGFR was comparable to healthy neonates by time of Norwood. Median age and weight at Norwood were 31 days and 3.34 kg. No survivors developed NEC or sustained AKI; 54% of survivors were discharged with tube feeding. Median ICU and hospital stays were 50 and 78 days. **Conclusion:** In this early experience, short-term outcomes of the rapid two-stage Norwood strategy are comparable to contemporary outcomes of the primary Norwood. However, as experience evolves, we believe this approach may increase survival due to improve end-organ function, with lower risks of morbidity to the heart, gut, brain, and kidneys. Larger studies with longer follow-up are needed to establish this potential benefit.

Keywords

HLHS, Rapid Bilateral Pulmonary Artery Banding, Delayed Norwood, Congenital Heart Disease, Single Ventricle

1. Introduction

Since its introduction in 1981, the Norwood procedure has transformed the management of hypoplastic left heart syndrome (HLHS) from a fatal condition to one compatible with long-term survival. However, despite improvement over early experience, the Norwood remains among the highest-risk operations in congenital cardiac surgery, with substantial perioperative morbidity including extracorporeal membrane oxygenation (ECMO), cardiac arrest, stroke, acute kidney injury (AKI) and necrotizing enterocolitis (NEC). Transplant-free survival for patients with HLHS also has not meaningfully improved over the past two decades [1]: more than 40% do not survive to adulthood, and 35-year transplant-free survival remains ~30%. In addition, long-term morbidity among survivors of HLHS is also considerable and includes chronic heart failure, protein-losing enteropathy, plastic bronchitis, neurodevelopmental impairment, chronic kidney disease, liver dysfunction, and gastrointestinal complications [2]. In the most recent publication from the landmark Single Ventricle Reconstruction (SVR) trial, death or major morbidities occurred in 87% [3].

Given these sobering results in the current era, we felt it was mandatory to review management options at our institution. Our group has previously reported the physiologic rationale for the strategy for a rapid two-stage Norwood, with rapid pulmonary artery banding (PAB) with delayed Norwood surgery beyond the neonatal period [4]. Importantly, the neonatal period represents a critical window of organ maturation characterized by hyperplastic growth of the heart, kidneys, lungs, and gastrointestinal tract, as well as neuronal proliferation and migration. Rapid PAB with maintenance of a patent ductus arteriosus (PDA) allows stabilization of hemodynamics, and delaying the Norwood beyond the neonatal period permits additional time for end-organ development, prior to exposure to cardiopulmonary bypass and complex surgical reconstruction. This strategy also facilitates neurodevelopmentally appropriate care, including preoperative enteral feeding and early parental-infant bonding. Maintaining PDA with prostaglandin (PGE_1), rather than stenting, may reduce trauma to the aortic arch, easier subsequent arch reconstruction, and avoid stent-associated complications.

Based on this rationale, we developed an institutional rapid two-stage Norwood strategy for patients with HLHS and its variants, consisting of bilateral PAB within the first three days of life, followed by delayed Norwood procedure at approximately 3 - 4 weeks of age. The study evaluates the short-term outcomes of this approach.

2. Methods

2.1. Patient Inclusion

We included neonates with HLHS or its variant admitted from December 2022-February 2025 who underwent rapid PAB and subsequent delayed Norwood at 3-4 weeks of age. **Figure S1** illustrates the approach for the rapid two-stage Norwood strategy.

Clinical perioperative and outcomes data were extracted from medical records. High pre-operative risk factors were defined as: 1) Prematurity <37 weeks, 2) Birth weight <2.5 kg, 3) Genetic anomalies, 4) Extracardiac anomalies, 5) RV dysfunction, 6) ≥Moderate tricuspid insufficiency, 7) Ascending aorta < 2 mm, 8) Intact/restrictive atrial septum, 9) Shock, 10) Invasive mechanical ventilation. Vasoactive inotropic score (VIS) was calculated according to Gaies *et al*. [5]. Neonatal mGFR was calculated based on Smeet *et al*. [6]: mGFR [ml/min per 1.73 m^2] = (0.31 × height [cm])/serum creatinine [mg/dl] based on length and the highest serum creatinine value obtained on each postnatal day until time of Norwood. Renal failure was defined as creatinine >1.5 mg/dL or tripling of creatinine >7 post-operative days, or dialysis. AKI was defined using the modified version of the neonatal Kidney Disease Improving Global Outcomes (KDIGO) and was assessed based on serum creatinine levels preoperatively and on the first to third postoperative days (PODs) [7]. Severe AKI was defined as KDIGO stage 2 or 3 (at least a 2× increase in serum creatinine from baseline). Baseline serum creatinine was defined as the lowest value before cardiac surgery.

This study was approved by Children's National IRB (CNCORE # Pro00015566). Categorical data were presented as frequencies and percentages. Continuous variables were reported as median (range).

2.2. Bilateral Pulmonary Arteries Band Procedure

Bilateral PAB were placed via median sternotomy. The bands were created by cutting 1 - 1.6 mm disks from a Gorte-Tex tube graft with a diameter of 3mm (<3 kg) or 3.5 mm (>3.5 kg) and were tightened with a single 6.0 Prolene suture.

2.3. Norwood Procedure

The Norwood procedure consisted of division of the PDA, division of the main pulmonary artery and side to side anastomosis of the ascending aorta, aortic arch augmentation using pulmonary artery homograft and atrial septectomy. Bilateral bands were removed, with internal Hegar dilation of the pulmonary arteries. Pulmonary blood flow was established with either mBTT shunt or RV-PA Sano conduit. One patient with an anomalous right subclavian artery from the main pulmonary underwent reimplantation of the anomalous artery and placement of a central shunt.

2.4. PGE_1 Dosing

The typical starting dose for PGE_1 was 0.01 mcg/kg/min. Ductal patency was assessed by echocardiography at least once weekly while patients remained on PGE_1.

PGE_1 could be increased to a maximum of 0.1 mcg/kg/min at the attending intensivist's discretion with echocardiographic or clinical concern for ductal constriction.

3. Results

3.1. Patient Characteristics

From December 2022 to February 2025 there were 22 neonates with single ventricle variants who underwent bilateral PAB (Figure 1). Six patients had extreme risk factors and/or underwent PAB late (>1 week after birth): 4 died, 1 patient survived to transplant and 1 survived to delayed Norwood. Sixteen patients underwent rapid PAB with intent for delayed Norwood. Three patients underwent rapid PAB and subsequently the Norwood at DOL 3 and 6 due to restrictive atrial septum requiring septectomy and one at DOL 15 due to failure to gain weight: all three survived and are now s/p SCPC. Thirteen total patients were included in the rapid two-stage Norwood criteria defined as rapid PAB and delayed Norwood at approximately 3 - 4 weeks of age. Of those, the median gestation age was $38^{5/7}$ ($37^{5/7}$-$39^{1/7}$) weeks. The median weight at birth was 3.13 (2.4 - 3.62) kg. 54% were males. Six patients (46%) had standard risks for the Norwood procedures, whereas 7 patients (54%) were considered high risk with one or more risk factors (Table 1). Table S1 outlines the cardiac defects and risk factors for each individual patient.

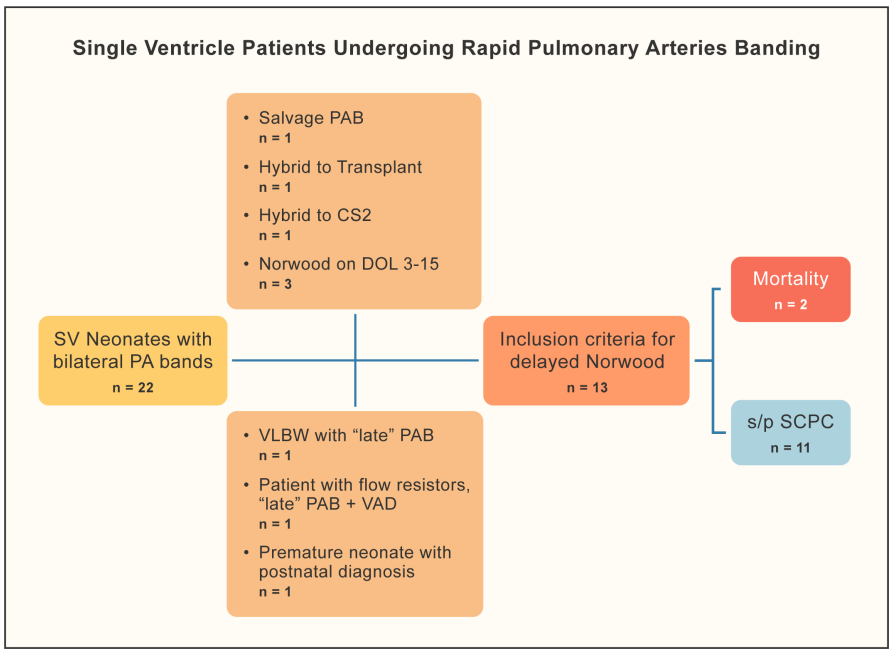


Figure 1. Single ventricle patients undergoing PAB during study period.

The median age at the time of PAB was 2 (1 - 5) days. One patient received a planned PAB at 5 days of age because of timing of transfer from another hospital; this patient was managed with the same intended strategy and was included in the analysis. At the time of PAB, 5 (38.5%) were receiving vasoactive, 3 (23.1%) were

receiving invasive mechanical ventilation, and 3 (23.1%) had shock with lactic acidosis (Table S2). Twelve patients had normal systemic systolic ventricular function and 1 had mildly depressed function (Table S3). Twelve had trivial/mild systemic atrioventricular valve regurgitation (AVVR) and 1 had moderate AVVR (Table S4). One patient developed heart block during a pre-operative cardiac CT resulting in E-CPR. The heart block resolved and the PAB were placed at the time of ECMO decannulation.

Table 1. Patients demographics and characteristics.

Variable	Median (range) or n (%) N = 13
Gestational Age	$38^{5/7}$ ($35^{5/7}$ - $39^{1/7}$ weeks)
Age at pulmonary artery banding	2 (1 - 5 days)
Weight at birth	3.13 (2.4 - 3.62 kg)
Sex	54% M 46% F
Race/Ethnicities	23% Caucasian, 31% AA, 38% Hispanic, 8% mixed
Risk factors*	1 (0 - 3)
Standard risk for Norwood	6 (46%)
High risk for Norwood (≥1 risk factors)	7 (54%)

Risk factors: 1) Prematurity <37 weeks, 2) Birth weight <2.5 kg, 3> Genetic anomalies, 4) Presence of extracardiac anomalies, 5) RV dysfunction, 6) ≥Moderate tricuspid insufficiency, 7) Ascending aorta < 2 mm, 8) Intact/restrictive atrial septum, 9) Shock, 10) Invasive mechanical ventilation.

3.2. Outcomes after Rapid PAB

Table 2 outlines the outcomes of patients after PAB. There was one delayed sternal closure due to hemodynamic instability. The median mechanical ventilation time was 3 (0 - 11) days. The median VIS score was 0 (0 - 10), 3 (0 - 12), 2 (0 - 11), 0 (0 - 8.5) at time of ICU arrival, 12 hours, 24 hours and 48 hours postoperative. Median PaO_2 was 42 - 45 mmHg at time CICU arrival, 12 hours, 24 hours, and at 48 hours. Median lactate values were normal across those same time points (Table 3). All patients had improved or stable ventricular function and AVVR after PAB. Following PAB, the immediate LPA band peak velocity on echocardiogram was 2.66 (2.1 - 3.5) m/s and the median RPA peak velocity was 2.89 (2.3 - 3.81) m/s (Figure S2).

Three underwent balloon atrial septostomy for restrictive atrial septum following PAB (one planned, two triggered by surveillance echocardiogram). Three showed PDA constriction on echocardiographic surveillance requiring PGE_1 escalation. One developed cardiac ischemia and cardiac arrest as a consequence of restrictive PDA in the setting of aortic atresia, requiring E-CPR and then subsequently delayed Norwood palliation from VA-ECMO.

Table 2. Patient outcomes between rapid PAB and delayed Norwood.

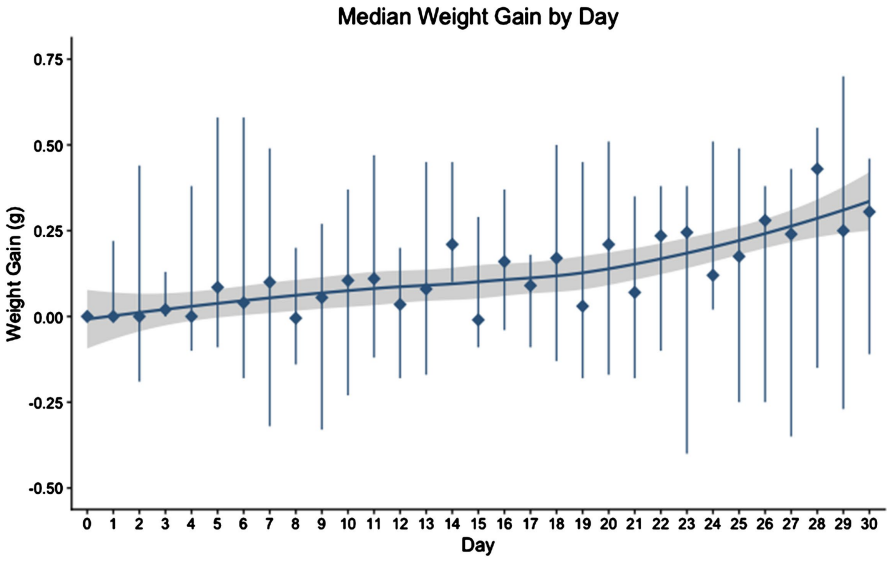
Variable	Median (range) or n (%) N = 13
Mechanical ventilation (days)	3 (0 - 11 days)
Chest tube duration	2 (1 - 9 days)
Arrhythmia	2 (15.4%)
Reintubation	3 (23%)
Seizure	0 (0%)
Stroke	1 (7.7%)
NEC	1 (8.3%)
Mediastinitis	0
Delayed sternal closure	1 (7.7%)
Sepsis	2 (15.3%)
Infection (bacteremia, pneumonia or UTI)	3 (23%)
Balloon atrial septostomy	3 (23%)
PDA constriction	3 (23%)
E-CPR	1 (7.7%)
Enterally fed prior Norwood	12/13 (92%)

Table 3. Physiologic outcomes after rapid PAB bands and delayed Norwood.

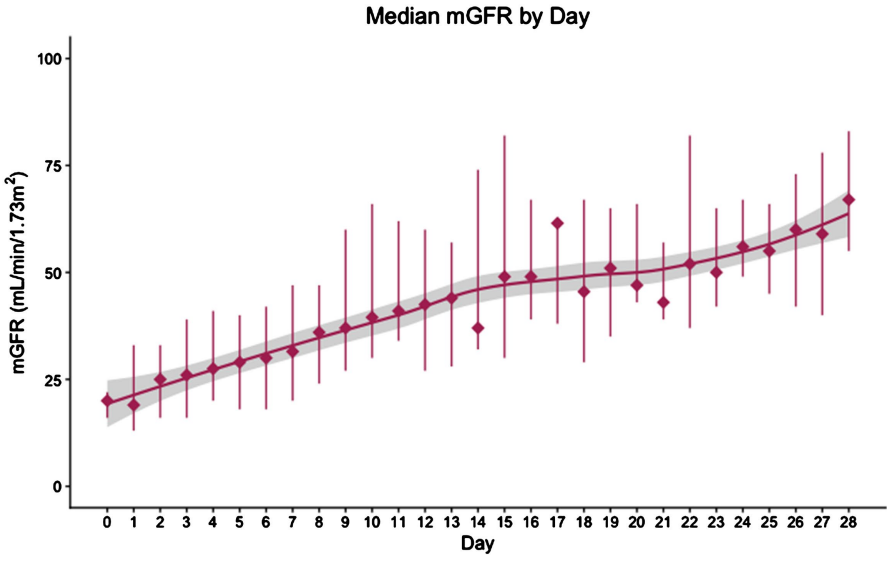
Outcomes after Rapid PAB					
Physiologic Outcomes	**ICU arrival (median, range)**	**12 hours (median, range)**	**24 hours (median, range)**	**36 hours (median, range)**	**48 hours (median, range)**
VIS	0 (0 - 10)	3 (0 - 12)	2 (0 - 11)	0 (0 - 9.5)	0 (0 - 8.5)
PaO_2 (mmHg)	42.7 (34.1 - 58.8)	45.4 (35.9 - 57.5)	43.15 (29.5 - 54)	42 (33.5 - 49.1)	46.5 (41.4 - 56)
Lactate (mmol/L)	2.43 (1.24 - 15.4)	2.53 (1.77 - 7.46)	2.59 (1.86 - 8.11)	1.80 (1.13 - 5.88)	1.61 (1.11 - 2.28)
Outcomes after delayed Norwood					
Physiologic Outcomes	**ICU arrival (median, range)**	**12 hours (median, range)**	**24 hours (median, range)**	**36 hours (median, range)**	**48 hours (median, range)**
VIS	8 (2 - 15.5)	9.75 (7 - 13)	7.88 (5 - 13.5)	7.5 (5 - 15.5)	7.5 (0 - 20.5)
PaO_2 (mmHg)	40.3 (33.1 - 45.6)	42.7 (33.3 - 47.1)	42.3 (35.7 - 49)	40 (35.6 - 48.7)	41.1 (34.8 - 45.4)
Lactate (mmol/L)	4.47 (1.48 - 18.27)	1.85 (0.94 - 5)	1.45 (0.87 - 2.31)	1.15 (0.57 - 1.6)	1.02 (0.51 - 1.59)

No perioperative seizures or strokes were observed after PAB. Two late strokes occurred: one was detected incidentally on routine pre-Norwood brain MRI, and the other was seen following the E-CPR event described above. NEC was also seen in this E-CPR patient, likely as a sequela of the ischemic event.

Most neonates in our cohort did not demonstrate significant weight gain in the first two weeks of life. All patients were variably enterally fed prior to delayed Norwood, although only 3 (23%) achieved exclusive oral feeding, while others were given a combination of supplemental tube feeding and/or TPN/IL to support calorie intake. There was a trend in positive weight gain after 2 weeks. At 28 days of life, there was a median weight gain of 430 (−150 - 550) grams (Figure 2(A)).



(A)



(B)

Figure 2. Weight gain and mGFR trend from birth and delayed Norwood. (A) Weight gain by day; (B) Glomerular filtration ratio by day.

Renal function improved rapidly after rapid PAB. Median mGFR at birth was 20 (16 - 22) mL/min/1.73m^2, with mGFR reaching 40 (31 - 62) mL/min/1.73m^2 by day 13 and normalizing to 67 (55 - 83) mL/min/1.73m^2 by day 28 (**Figure 2(B)**).

Temporal review of the data suggested an "learning curve" over the course of this experience (**Figures S3(A)-(E)**). As institutional experience was achieved caring for these patients, there was a trend toward decreased postoperative vasoactive administration over time. There were also concerted efforts to reduce postoperative mechanical ventilation duration, and the last patient in the series was successfully extubated in the operating room after PAB. Similarly, there was a trend toward earlier introduction of enteral feeding, resulting in more successful exclusive oral feeding prior to the delayed Norwood in later patients in the series.

3.3. Outcomes after Norwood

Table 4 outlines the characteristics of patients at time of delayed Norwood. The median age was 31 (20 - 36) days. Median weight was 3.34 (2.56 - 4.34) kg. Nine (70%) underwent Norwood with Sano shunt. Three (23%) had mBTT shunts and one patient had a central shunt. All patients underwent delayed sternal closure.

The median vasoactive scores following delayed Norwood were 8, 9, 7.25 and 7.5 at time of CICU arrival, 12 hours, 24 hours and 48 hours, respectively. Median lactate was 4.47 mmol/L (1.48 - 18.27) on ICU arrival, decreasing to 1.85 (0.94 - 5), 1.45 (0.87 - 2.31), 1.15 (0.57 - 1.6) and 1.02 (0.51 - 1.59), respectively across those time points (**Table 3**).

Table 4. Patient and surgical characteristics at the time of Norwood.

Characteristics	Median (range) or N (%)
Age (days)	31 (20 - 36)
Weight (kg)	3.34 (2.56 - 4.34)
mGFR (mL/min/1.73 m^2)	58 (40 - 83)
Shunt type	
mBTT	3 (23%) 1 (3 mm), 2 (3.5 mm)
Sano	9 (70%) 4 (4 mm), 4 (5 mm), 1 (6 mm)
Central	1 (7%) (3.5 mm)
Cardiopulmonary bypass (min)	233 (163 - 339)
Aortic cross clamp (min)	91 (43 - 173)
Selective Cerebral Perfusion (min)	10.5 (8 - 65)

Table 5 outlines short-term outcomes of patients after delayed Norwood. Two died prior to discharge (15.4%), both due to severe neurologic injuries after E-CPR events. Four underwent VA-ECMO support (30.1%), three of whom (23%)

received E-CPR. Five had seizures: 2 (15.4%) had perioperative seizure (<48 hours after surgery) and 3 (23%) developed clinical seizure later. Five (38.5%) had hemorrhagic or ischemic stroke postoperatively. There was no post-operative NEC. There was no persistent AKI among survivors. Five (38%) developed stage 1 AKI and four (31%) developed severe AKI (KDIGO stage 2 - 3) postoperatively. Renal function recovered in all but one patient, who died with persistent renal failure. Nine (82%) survivors were diagnosed with vocal cord palsy. Median ICU LOS and hospital LOS was 50 (38 - 73) and 78 (58 - 196) days, respectively; one patient did not get discharged until after the bidirectional Glenn procedure with a total LOS of 196 days. Six survivors (54%) were discharged with tube feeds.

Table 5. Patient short-term outcomes after delayed Norwood.

Outcomes	Median (range) or n (%)N = 13
Total ICU LOS (days)	50 (38 - 73)
Total hospital LOS (days)	78 (58 - 196)
Total mechanical ventilation (days)	8.2 (2.6 - 39 days)
Delayed sternal closure (days)	2 (1 - 14 days)
Mortality	2 (15.4%)
ECMO	4 (30.1%)
Cardiac arrest (E-CPR)	3 (23%)
Stroke	5 (38.5%)
Post operative AKI (within 3 days post op)	
Stage 2 KDIGO criteria	1 (7.7%)
Stage 3 KDIGO criteria	3 (23%)
Renal Failure (>7 days post op)	1 (7.7%)
Perioperative Seizure* (<48 hrs)	2 (15.4%)
Late Seizure	3 (23%)
NEC	0 (0%)
Culture Positive Sepsis	3 (23%)
Chylothorax	0
Vocal cord paresis (VCP)**	9 (82%)
Paralyzed diaphragm	1 (7.7%)
NG/GT feeding at discharge	6 (54% of survivors)

*All patients were monitored with continuous 48hr EEG postoperatively; ** VCP was diagnosed by ultrasound or flexible endoscopy in survivors.

4. Discussion

In this study, we describe our early institutional experience with a novel rapid two-stage Norwood strategy consisting of rapid PAB, followed by delayed Norwood beyond the neonatal period. In this initial experience, the outcomes were not what we had hoped, with mortality and major morbidities rates similar to those reported in contemporary series. However, there were several findings that suggest meaningful potential benefits of this approach. PAB for approximately 3-4 weeks did not appear to complicate the subsequent Norwood operation and there were encouraging trends in improved renal function, feeding tolerance, reduction in NEC, and overall physiologic resilience, factors that may have important implications for longer-term outcomes and recovery. These findings suggest that, when carefully implemented, this strategy can provide early physiologic stability while allowing for maturation of vulnerable end-organ systems prior to exposure to cardiopulmonary bypass and the Norwood procedure.

Despite a relatively high-risk cohort, rapid PAB achieved effective hemodynamics stabilization and control of pulmonary blood flow, as evidenced by a median PaO_2 of 42mmHg and low lactate immediately post-operative and thereafter. In all patients, PAB was associated with improvement of pre-existing AVVR or preservation of AV competence, while systolic ventricular function remained stable or improved following PAB. Vasoactive support need was also low postoperatively in most patients and effectively decreased over time as we gained increased institutional experience with the post-operative physiologic trajectory.

Postnatal weight gain after PAB was modest. Significant weight gain was not observed within the first two weeks, in line with population studies demonstrating that 14 - 24% and 5 - 8% of term neonates remain below birth weight at 14 and 21 DOL, respectively [8]. Early in our experience, limited weight gain following PAB raised concern for inadequate control of pulmonary blood flow and heart failure. However, longitudinal observation reinforced that weight gain is an unreliable metric in banded physiology and must be interpreted in the context of postnatal age and additional signs of poor hemodynamics. Failure to gain weight in the first two weeks after banding should not, in isolation, be considered evidence of strategy failure.

A major strength of this approach was the ability to establish enteral feeding in patients prior to Norwood. While only 3 patients later in the series met full nutritional requirements by mouth, all neonates were invariably enterally fed between PAB and delayed Norwood. Preoperative enteral nutrition likely contributed to gastrointestinal protection, as no patients developed post-Norwood NEC, a complication reported in 5 - 37% of conventional Norwood [9]-[11]. Nearly half of surviving patients were discharged home without enteral feeding tubes, comparing favorably with published rates following conventional Norwood. The high incidence of vocal cord paresis (82%) in this cohort emerged as a significant contributor to feeding difficulties, limiting oral feeding success and prolonging hospital length of stay. To address this challenge, we have implemented a compre-

hensive screening program focused on early identification and intervention to improve feeding outcomes [12].

Renal function recovery provided the strongest physiologic justification for delayed Norwood. In our cohort, mGFR at birth was comparable to healthy term newborns [6]. However, in contrast to healthy neonates, who typically demonstrate a doubling of mGFR within five days of life, our patients did not exhibit meaningful improvement until approximately two weeks. Renal function continued to improve rapidly thereafter with normal comparative mGFR by 28 days of age. These findings underscore the vulnerability of the kidneys in neonates undergoing conventional Norwood, a period of relative renal insufficiency. This observation aligns with the lower incidence of sustained AKI in our cohort compared to published literature for conventional Norwood [13]: 23% developed AKI immediately post-operative (stage 3 NKIGO criteria), however, AKI was transient, and only one non-surviving patient had sustained AKI >7 days. These findings suggest that delaying the Norwood operation until relative renal maturation may mitigate perioperative AKI.

One of the most consequential learning points from this series was the recognition of insidious PDA constriction during prolonged PGE_1 administration. Three developed ductal narrowing detected through routine echocardiography. These events prompted protocolized echocardiographic surveillance and earlier PGE_1 escalation thresholds in later patients. One catastrophic cardiac arrest event highlights the potential consequences of combined relative ductal constriction and aortic atresia, reinforcing the narrow therapeutic margin in prolonged ductal-dependent physiology and the need for vigilant, anticipatory management.

PAB effectively protected the pulmonary vasculature while allowing for modest interval pulmonary artery growth while awaiting the delayed Norwood. As expected, band gradients increased over time, with median peak velocities >4.0 m/s, consistent with relatively low distal pulmonary artery pressures. These findings support two important observations: first, the bands effectively protected the distal pulmonary vasculature; and second, there was modest interval pulmonary artery growth during the interstage waiting period that allowed patients to "grow" into the bands. Concerns remain regarding potential pulmonary artery distortion and implications for future Fontan completion; ongoing follow-up in this cohort will therefore be essential to determine the long-term impact of prolonged banding on pulmonary artery development.

Overall, the survival rate was 85%, comparable to contemporary Norwood outcomes. Nevertheless, rates of cardiac arrest, ECMO, stroke, and seizures in our cohort exceeded those reported in the literature. However, these adverse events must be considered in the context of the prolonged inpatient course, extended PGE_1 exposure, and heightened neurologic surveillance that are intrinsic to this staged approach, that may have led to increased events detection. Importantly, we believe as experience with this strategy grows, targeted refinements in perioperative management and surveillance protocols will reduce the incidence of these

complications and further improve outcomes.

Notably, 4 out of 13 (30%) patients in our cohort were supported with ECMO post-Norwood, with 3 receiving E-CPR. One patient required E-CPR prior to PAB due to heart block and later experienced two distinct late postoperative cardiac arrests after Norwood. Another patient, who sustained a post-PAB cardiac arrest due to a restrictive PDA, subsequently experienced two postoperative arrests after Norwood, attributed to residual ischemic myocardial injury from the initial event: one in the perioperative period and another event weeks later, both requiring E-CPR. These events shared common features, including post-operative neoaortic valve insufficiency, conduction abnormalities, and presumed occult residual ischemic myocardial injury. Recognition of this recurrent risk profile emerged over the course of this experience has since informed enhanced perioperative vigilance, refined risk stratification, and lower thresholds for early intervention. It is worth noting that, despite these severe adverse events, overall survival to discharge remained acceptable, highlighting both the physiologic resilience of these infants undergoing the delayed Norwood and the capacity for recovery when rapid and adequate circulatory support is provided.

A major tradeoff associated with this strategy is prolonged intensive care and hospital length of stay. In our cohort, the median ICU LOS and hospital LOS were 50 days and 78 days, respectively, consistent with the recently reported national trends in patients undergoing the delayed Norwood [14]. By comparison, aggregate data from the SVR trial showed a median ICU LOS and hospital LOS of 14 days and 24 days [15]. Prolonged hospitalization increases the risk of infection, resource utilization, family stress, and financial burden. However, extending the period of physiologic stability before the Norwood procedure may provide caregivers with valuable time for parent-infant bonding and adjustment, potentially reducing parental stress and improving preparation for this high-risk procedure. Importantly, there must be intentional efforts and interventions to support a developmentally appropriate environment during this extended inpatient care period [16]. While the additional inpatient care pre-Norwood remain necessary, there are ongoing efforts focused on reducing post-operative and overall LOS.

Despite these challenges, short-term outcomes in this series of patients undergoing the rapid two-stage Norwood appear similar to conventional management, with evidence of preserved renal and gastrointestinal function and improved end-organ maturation prior to Norwood palliation. While these findings must be interpreted cautiously given the small sample size and the learning curve that accompanies implementing a new strategy, they provide important signals that merits further investigation. The potential long-term benefit of protecting vulnerable organ systems during this critical developmental window may translate into improved resilience following Norwood palliation and, ultimately, improved long-term vitality.

5. Limitations

This study is limited by its retrospective and descriptive nature, small sample size,

significant patient variability, and the inherent challenges of evaluating a novel strategy during early implementation. Long-term outcomes including rates of re-intervention, pulmonary artery growth, Fontan completion, neurodevelopmental status, and late morbidity, are critically important and are currently being collected prospectively for future analysis.

6. Conclusions

In this early experience, the rapid two stage Norwood demonstrated comparable short-term survival, with improved organ function. While this approach is associated with a substantial learning curve and prolonged hospitalization, we believe that this strategy may provide improvement of cardiovascular, renal and neurologic function that allows patients to survive with lower risks of morbidities to the heart, gut, brain and kidneys. Further experience is important to refine patient selection and management and to determine whether the potential benefits apply broadly or primarily to specific subgroups of neonates with HLHS.

Author Contributions

Conceptualization, BNP, GW and Yd'U.; methodology, BNP; formal analysis, BNP; investigation, BNP; data curation, BNP; writing—original draft preparation, BNP; writing—review and editing, GW, AL, AT, MD, SB, MTD, RM, Yd'U.; supervision, GW, Yd'U; All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Supplementary Material

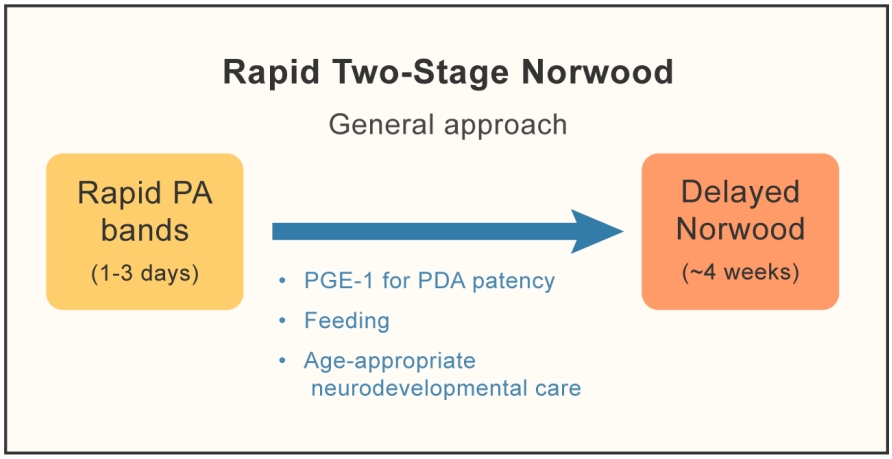


Figure S1. Approach to rapid two-stage Norwood.

Table S1. Patient diagnosis, risk factors and status.

Patient	Primary Diagnosis	Additional cardiac anomalies	Risk Factors	Status
1	HLHS (MS/AA)	Coronary fistula	Pre-band Shock	S/p SCPC
2	HLHS (MS/AA)		Pre-band Shock	S/p SCPC
3	Unbalanced AVC, coarctation	Heterotaxy, interrupted IVC		S/p SCPC
4	HLHS (MS/AA)	Coronary sinusoids		S/p SCPC
5	HLHS (MS/AA)			S/p SCPC
6	DORV, Hypoplastic LV (MA/AA)	Heterotaxy, interrupted IVC	<2 mm ascending aorta	Died
7	Malposed great arteries, Hypoplastic right heart, aortic atresia		<2 mm ascending aorta	S/p SCPC
8	HLHS (MS/AA)			S/p SCPC
9	HLHS (MS/AS)		Imperforate anus <37 weeks EGA <2.5 kg	S/p SCPC
10	Double inlet LV, hypoplastic RV, hypoplastic arch and coarctation	- Anomalous right subclavian from pulmonary artery - Pre-operative heart block	Pre-band shock/E-CPR	S/p SCPC
11	HLHS (MS/AA)	- Decompression levo-atrial cardinal vein - Anomalous LUPV	<37 weeks EGA	Died
12	Unbalanced AVC, aortic arch hypoplasia			S/p SCPC
13	HLHS (MA/AA)			S/p SCPC

Table S2. Clinical status at time of rapid PAB.

Clinical status	n (%) N = 13
Receiving vasoactive	5 (38.5%)
Invasive mechanical ventilation	3 (23.1%)
Shock	3 (23.1%)
E-CPR (due to heart block)	1 (7.7%)
Elective PA banding	7 (53.8%)

Table S3. Echographic systolic systemic ventricular function over time.

	Pre-PAB	Post-PAB	Pre-Norwood	Post-Norwood
1	Lower limit of normal	Normal function	Normal function	Normal function
2	Normal function	Normal function	Normal function	Normal function
3	Normal function	Normal function	Normal function	Normal function
4	Normal function	Normal function	Normal function	Normal function
5	Normal function	Normal function	Normal function	Normal function
6	Normal function	Normal function	Normal function	Normal function
7	Normal function	Normal function	Normal function	Normal function
8	Normal function	Normal function	Normal function	Normal function
9	Mildly depressed	Normal function	Normal function	Normal function
10	Normal function	Normal function	Normal function	Normal function
11	Normal function	Normal function	Normal function	Normal function
12	Normal function	Normal function	Normal function	Normal function
13	Normal function	Normal function	Normal function	Normal function

Table S4. Echographic systemic atrioventricular valvular function (Regurgitation quality) over time.

	Pre-PAB	Post-PAB	Pre-Norwood	Post-Norwood
1	Mild	Trivial	Trivial	Mild
2	None	Trivial	Trivial	Trivial
3	Mild	Trivial	Trivial	Trivial
4	Trivial	Trivial	Mild	Trivial
5	Moderate	Mild	Mild	Trivial
6	Mild	Trivial	Mild-moderate	Mild
7	None	Trivial	Trivial	Trivial

Continued

8	Mild	Trivial	Trivial	Mild
9	Trivial	Trivial	Mild	Mild
10	Trivial	Trivial	none	Trivial
11	Trivial	Trivial	Trivial	Mild
12	Trivial	Trivial	Mild	Mild
13	Trivial	Trivial	Trivial	Mild

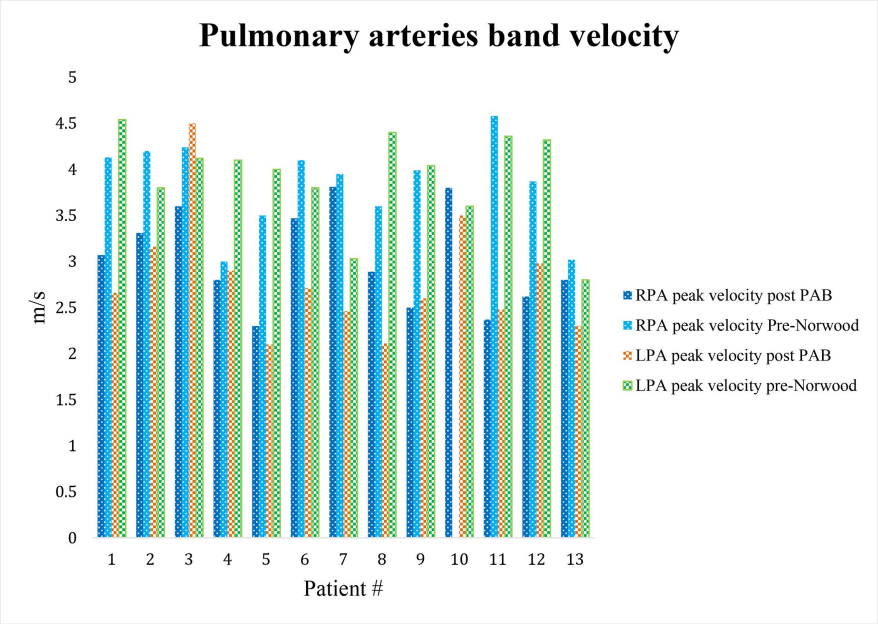
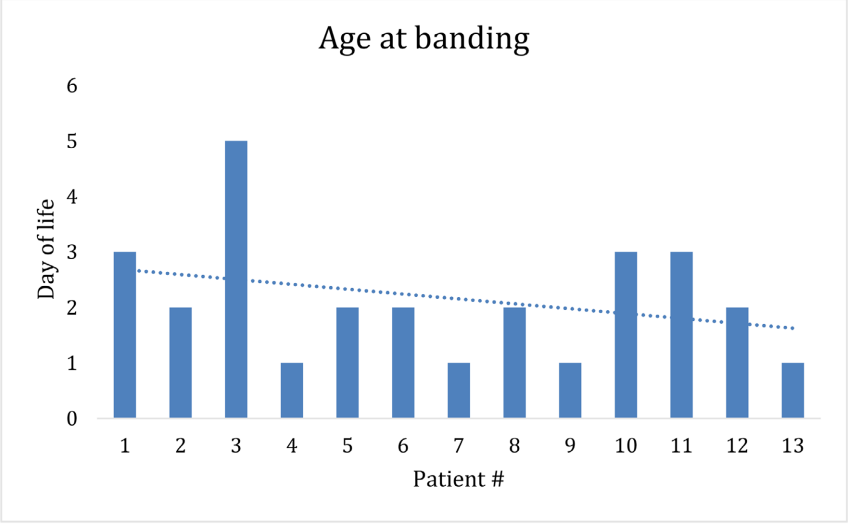
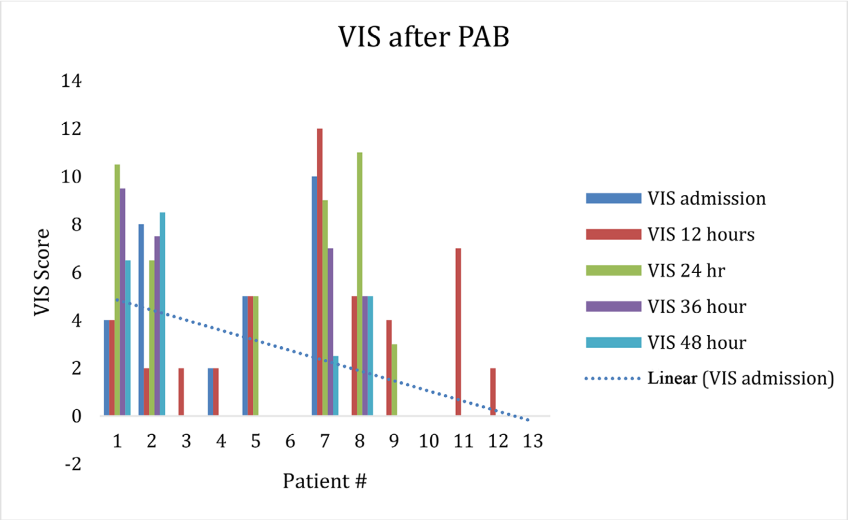


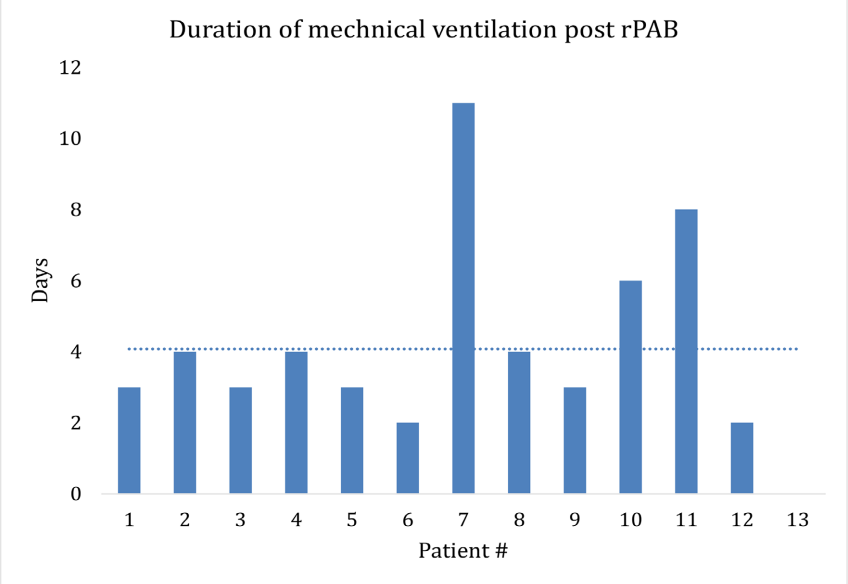
Figure S2. Pulmonary arteries band echocardiographic gradient before and after rapid PAB.



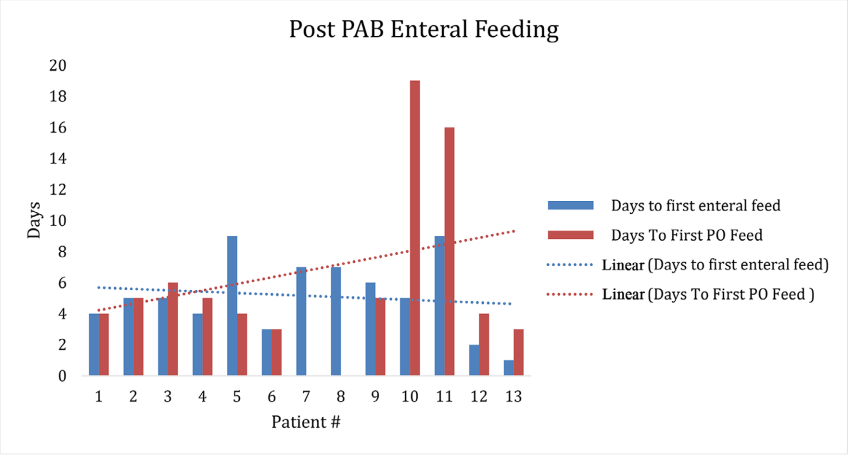
(A)


VIS after PAB
VIS Score
Patient #
VIS admission
VIS 12 hours
VIS 24 hr
VIS 36 hour
VIS 48 hour
Linear (VIS admission)

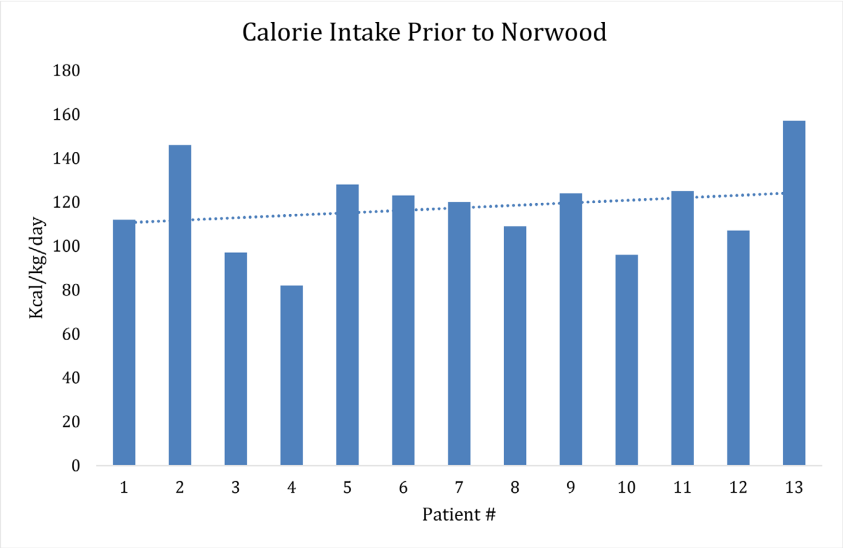
(B)


Duration of mechnical ventilation post rPAB
Days
Patient #

(C)


Post PAB Enteral Feeding
Days
Patient #
Days to first enteral feed
Days To First PO Feed
Linear (Days to first enteral feed)
Linear (Days To First PO Feed)

(D)



(E)

Figure S3. Learning curve of surgical and ICU post operative care over time. (A) Age at time of bilateral pulmonary artery banding over time; (B) Post operative vis after rapid pulmonary artery bands; (C) Mechanical ventilation duration post rapid pulmonary arteries bands; (D) Time to enteral feeding post rapid pulmonary arteries bands; (E) Maximal calorie intake for each patient over time prior to delayed Norwood.