



# Surgical Management of Hypoplastic Left Heart Syndrome

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## Introduction

Congenital heart disease is the most common birth defect [1]. The incidence is about 40,000 United States (US) births per year and 1,000,000 worldwide births per year [2, 3]. It accounts for approximately 4.2% of all neonatal deaths [4]. The most common severe form of congenital heart disease is hypoplastic left heart syndrome (HLHS), affecting almost 1000 US births per year [5].

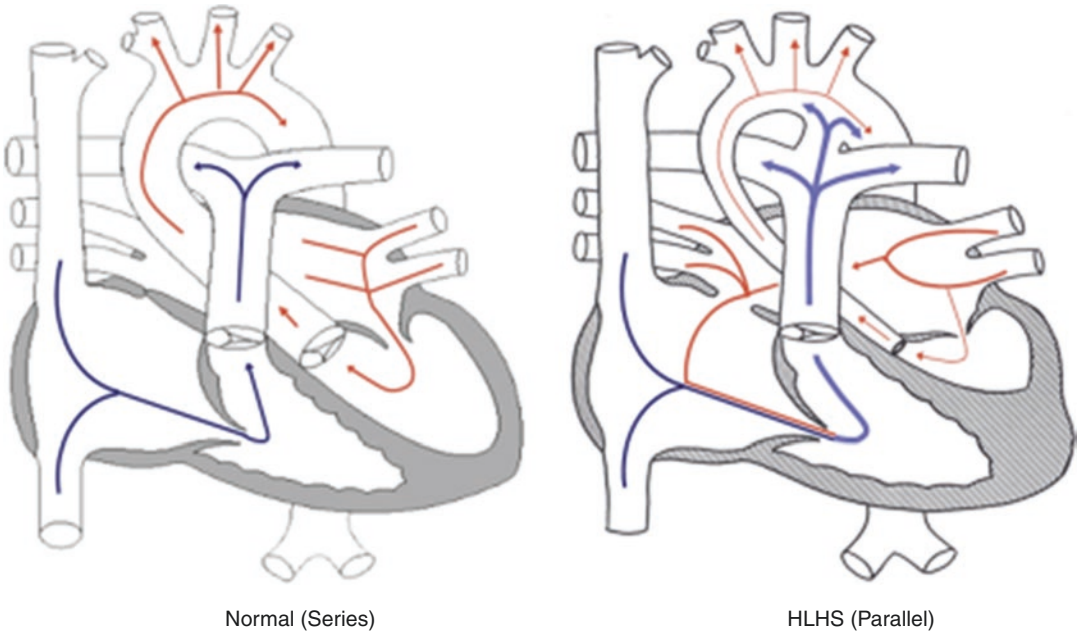
Hypoplastic left heart syndrome is defined by underdevelopment of the left side of the heart with associated systemic outflow obstruction. This consists of mitral stenosis or atresia, a non-apex-forming hypoplastic left ventricle, aortic stenosis or atresia, a hypoplastic ascending and arch aorta, coarctation of the aorta, and a patent ductus arteriosus. Although not strictly classified as a single ventricle or functionally univentricular heart by the Congenital Heart Surgery Nomenclature and Database Project [6], it shares common pathophysiology and treatment with these lesions. In contrast to normal hearts with a series circulation,

there are intracardiac shunt(s) present with mixing of blood in a parallel circulation (Fig. 7.1). This produces abnormal systemic oxygen delivery and volume loading of the functional single ventricle. The clinical presentation depends on the degrees of systemic and pulmonary outflow obstruction determining the systemic (SBF) and pulmonary blood flow (PBF). Patients with a balanced circulation may initially be asymptomatic. Those with inadequate PBF will present with cyanosis, and those with excessive PBF will present with heart failure. Those with systemic outflow obstruction significant enough to require ductal patency for systemic output, such as HLHS, may present in shock. These factors contribute to the poor prognosis if left untreated.

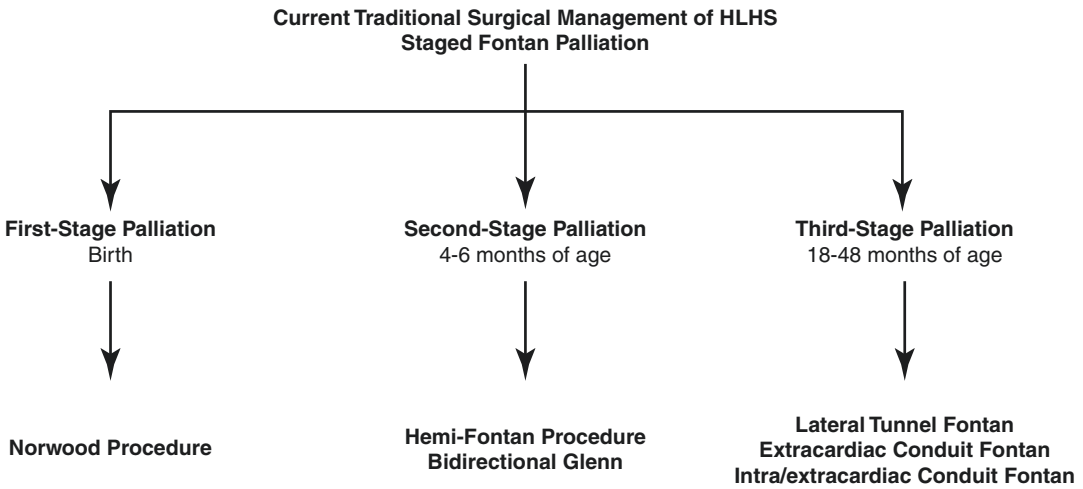
Early HLHS patients had no or few surgical options. This diagnosis was universally fatal. However, the field of congenital heart surgery has made great advancements over the past 40 years. This progress can be particularly seen in these patients. Early treatment included interest in primary heart transplantation [7, 8] and the development of the Norwood procedure [9]. Current traditional surgical management of HLHS consists of staged palliation to a Fontan circulation (Fig. 7.2). This is composed of the Norwood procedure at birth, second-stage superior cavopulmonary connection at typically 4–6 months of age, and a completion Fontan procedure at 18–48 months of age.

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**Fig. 7.1** A comparison of a normal series circulation to a HLHS parallel circulation



**Fig. 7.2** Current traditional surgical management of HLHS consists of staged palliation to a Fontan circulation

Based on this standard management, outcomes have dramatically improved. The aggregate outcomes of staged palliation of all participants of the Society of Thoracic Surgeons Congenital Heart Surgery Database (STS CHSD) were reported in 2016. The aggregate operative mortality for the Norwood procedure

was 15.6%, the hemi-Fontan or bidirectional Glenn procedure was 2.1%, and the Fontan procedure was 1.4%. The aggregate average post-operative length of stay for the Norwood procedure was 42.2 days, the hemi-Fontan or bidirectional Glenn procedure was 13.8 days, and the Fontan procedure was 13.4 days [10]. In

experienced centers, hospital survival following the Norwood procedure has been reported greater than 90% [11].

Despite these advances, there is still significant morbidity and mortality associated with HLHS. This has led to investigation into new and alternative therapies. As a result, there is substantial practice pattern variation among institutions and between individual surgeons, cardiologists, and intensivists.

Wernovsky et al. conducted an online survey in 2007 evaluating management of HLHS in 52 centers worldwide thought to manage 1000 neonates with HLHS annually. The results demonstrated considerable variability in most parameters. Some results favored a consensus opinion, whereas others favored equivocal or even controversial conclusions. Of note, the type of intensive care unit in which patients were managed, both before and after surgery, varied widely among centers [12]. Pasquali et al. then conducted a study in 2012 to evaluate practice pattern variation in perioperative care of neonates undergoing the Norwood procedure using the Single Ventricle Reconstruction (SVR) trial dataset. This also demonstrated significant variability in preoperative, intraoperative, and postoperative variables (Table 7.1) [13]. However, of particular interest, significant differences also existed for in-hospital mortality and transplantation between centers. One may then theorize that practice pattern variation and current controversies in the management of these patients may be partially responsible for these differences. Therefore, if best practices can be identified, hopefully outcomes for HLHS patients may improve. This has already been demonstrated in adult cardiac surgery with the Michigan Society of Thoracic and Cardiovascular Surgery (MSTCVS) [14] and Northern New England Cardiovascular Disease Study Group [15]. Through adoption of practices used by high-performing centers, variation in care was reduced, outcomes were improved, and hospital costs lowered. Similar efforts are now being made through the National Pediatric Cardiology Quality Improvement Collaborative (NPC-QIC) [16].

**Table 7.1** Practice pattern variation in perioperative care of neonates undergoing the Norwood procedure using the Single Ventricle Reconstruction (SVR) trial dataset. The range is the differences in practice between each center. This demonstrates significant variability in preoperative, intraoperative, and postoperative variables. (Adapted from Pasquali et al. [13]) (*DHCA* deep hypothermic circulatory arrest, *ECMO* extracorporeal membrane oxygenation, *ICU* intensive care unit, *HCT* hematocrit, *RCP* retrograde cerebral perfusion)

Practice pattern variation	
<b>Preoperative variables</b>	
Fetal diagnosis	55–85%
Intubation	29–91%
<b>Intraoperative variables</b>	
Total bypass support time	74–189 min
Aortic cross-clamp time	33–73 min
DHCA only	3–100%
RCP only	3–93%
Lowest HCT	22–41%
Classic arch reconstruction	41–100%
<b>Postoperative variables</b>	
ICU stay	9–44 days
Hospital stay	19–44 days
Ventilator time	4–16 days
Open sternum	35–100%
ECMO	7–35%
Enteral tube	2–100%
Home monitoring	1–100%
Death or transplant during Norwood hospitalization	7–39%

Another controversial topic is regionalization of care to centers of excellence. Using the 2003 Kids' Inpatient Database, hospital mortality for the Norwood procedure and arterial switch operations were studied as a function of institutional volume. A total of 624 Norwood procedures performed at 60 hospitals, with a case range of 1–31 operations a year at each site, were evaluated. An inverse relationship was demonstrated between institutional volume and mortality with 35%, 26%, and 17% mortality in hospitals performing 2 per year, 10 per year, and 20 per year, respectively [17]. Using the STS CHSD, 2555 patients undergoing the Norwood procedure at 53 centers by a total of 111 surgeons were also evaluated. This demonstrated that lower center and surgeon volume were associated with higher mortality [18]. To better understand these differences, a large analysis of the 2006–2009 STS CHSD was

**Table 7.2** The current controversies in the surgical management of HLHS which will be the focus of this chapter

Current controversies
Fetal cardiac intervention
First-stage palliation
Norwood procedure
Shunt type
Deep hypothermic circulatory arrest versus regional cerebral perfusion
Delayed sternal closure
Hybrid Norwood
Postoperative management
Second-stage palliation
Third-stage palliation
Role of a fenestration
Mechanical circulatory support
Transplantation

performed including 40,930 patients at 72 centers. Interestingly, there was no difference in complication rates between high, middle, and low mortality hospitals. However, low mortality hospitals had the lowest failure to rescue rate (the probability of death after a complication) [19]. This has now become a well-known phenomenon that has been demonstrated across many other surgical specialties [20].

As is clearly evident, multiple current controversies exist regarding surgical management of HLHS (Table 7.2). They will therefore be discussed in the remainder of this chapter.

#### Patient Scenario

*A 2.5 kg male born at 35 weeks gestational age with a postnatal diagnosis of HLHS presents from an outside hospital in shock. The patient is intubated and begun on prostaglandin infusion and vasoactive support. A transthoracic echocardiogram demonstrates a nonrestrictive atrial septum, HLHS consisting of mitral stenosis and aortic stenosis, a 3 mm ascending aorta, and no evidence of coronary sinusoids. The resident physician caring for this baby asks what surgical options are available as well as if something could have prevented or mitigated the severity of this condition.*

## Fetal Cardiac Intervention

Prenatal diagnosis of HLHS has increased. Since 2012, 82% of Norwood procedures performed at the University of Michigan had a prenatal diagnosis. This allows surveillance of high-risk lesions, the opportunity for counseling, optimal timing and location of delivery, and better transition to postnatal care. Although it has not clearly demonstrated improved survival [21], there is evidence of decreased morbidity [22]. In addition, it offers the consideration for fetal cardiac intervention (FCI) performed in select quaternary referral centers.

Fetal cardiac interventions are reserved at this time for HLHS patients with either aortic valve stenosis or a restrictive/intact atrial septum. It has been proposed that aortic valve stenosis in a fetus with an initially normal-sized left ventricle can progress to HLHS. Therefore, the hope is that fetal balloon valvuloplasty can prevent this progression. It is currently selectively utilized in patients who are not yet thought to have HLHS or in patients who may have potential for biventricular repair [23–33].

A restrictive or intact atrial septum is a known risk factor for HLHS [34]. It leads to pulmonary venous obstruction and irreversible pulmonary vascular changes that are unfavorable to a patient destined for staged Fontan palliation. Therefore, the hope is that fetal balloon atrial septostomy or atrial septal stent placement can prevent these changes [35, 36]. Although these therapies have shown some promising results, additional work is needed as they carry high risk with an estimated procedural fetal loss at approximately 10–15% [21].

## First-Stage Palliation

### Norwood Procedure

First-stage palliation for HLHS has traditionally been the Norwood procedure [9]. This procedure is performed within the first 7–14 days of life via a median sternotomy using cardiopulmonary bypass. The three goals of the procedure are to

provide unobstructed pulmonary venous return, unobstructed systemic outflow, and adequate, but restricted, pulmonary blood flow (Table 7.3). Unobstructed pulmonary venous return is achieved by an atrial septectomy which creates a nonrestrictive atrial septal defect to allow pulmonary venous return to the dominant right ventricle. Unobstructed systemic outflow is accomplished by connecting the dominant right ventricle to the systemic circulation. Initially, the ascending aorta and aortic arch are reconstructed to alleviate systemic arterial outflow obstruction. The main pulmonary artery is then divided, and the pulmonary root is connected to the augmented ascending aorta. Therefore, the right ventricle becomes the systemic ventricle as cardiac output will flow through the pulmonary (neo-aortic) valve into the ascending aorta. Our preference is allograft patch augmentation under hypothermic circulatory arrest without regional cerebral perfusion. Lastly, adequate and restricted pulmonary blood flow is necessary. This is achieved by creation of a systemic-to-pulmonary artery shunt, which replaces pulmonary blood flow from the native main pulmonary artery and patent ductus arteriosus. Options include a classic Blalock-Taussig shunt, modified Blalock-Taussig shunt (MBTS), central

aortopulmonary shunt, or right ventricle-to-pulmonary artery shunt (RVPAS).

## Shunt Type

Shunt type has been an actively investigated topic. The two main types used today are the MBTS and RVPAS, at the discretion of the operating surgeon. The MBTS provides PBF from the innominate artery to the right pulmonary artery using a polytetrafluoroethylene (PTFE) graft, typically 3.0–4.0 mm in size. Our preference is a 3.5 mm non-ringed and non-stretch PTFE graft. The RVPAS provides PBF from the right ventricle to the central pulmonary arteries using a graft. Our preference is a ringed PTFE graft, typically 5.0 or 6.0 mm in size, depending on the size of the patient. The proximal anastomosis can be sutured to the right ventriculotomy or placed within the ventricular cavity using a transmyocardial technique [37]. The distal anastomosis can similarly be performed either ways [38].

The MBTS had been the traditional shunt type despite an early description of the RVPAS by Norwood [39]. However, the RVPAS was popularized in the early 2000s by Kishimoto and Sano [40–43]. As a result, it is often referred to as the Sano shunt or modification. The theoretical advantages of the RVPAS are noncontinuous shunt flow only in systole without diastolic runoff; improved diastolic systemic perfusion leading to improved coronary blood flow, hemodynamic stability, and end-organ perfusion; and improved survival. The theoretical disadvantages are less PBF leading to more cyanosis, less pulmonary artery (PA) growth with more interventions, and a right ventriculotomy with decreased systemic ventricular function and increased arrhythmogenicity (Table 7.4).

A landmark study, the SVR trial, was therefore performed to attempt to answer the impact of shunt type. The Pediatric Heart Network (PHN), funded by the National Heart, Lung, and Blood Institute (NHLBI), sponsored this trial. The SVR trial was a multicenter, randomized clinical trial of 549 neonates with HLHS or other single right ventricle anomalies who underwent either a

**Table 7.3** The goals of first-stage palliation and how they are achieved in the traditional versus hybrid Norwood procedures (PA, pulmonary artery; PDA, patent ductus arteriosus; PGE, prostaglandin)

Goals of first-stage palliation		
Goal	Traditional Norwood	Hybrid Norwood
Unobstructed pulmonary venous return	Atrial septectomy	Atrial septostomy or atrial septal stent
Unobstructed systemic outflow	Connect dominant right ventricle to aorta Aortic arch reconstruction	PDA stent (transthoracic or percutaneous) or PGE infusion
Adequate and restricted pulmonary blood flow	Systemic-to-pulmonary artery shunt	Bilateral PA bands



**Table 7.4** The theoretical advantages and disadvantages of the right ventricle-to-pulmonary artery shunt at the Norwood procedure. (PA, pulmonary artery; PBF, pulmonary blood flow)

Theoretical advantages and disadvantages of the right ventricle-to-pulmonary artery shunt	
Advantages	Disadvantages
Noncontinuous shunt flow in systole	Less PBF
No diastolic runoff	More cyanosis
Improved diastolic systemic perfusion	Less PA growth
Improved coronary blood flow	More PA interventions
Improved end-organ perfusion	Right ventriculotomy
Hemodynamic stability	Decreased systemic ventricular function
Improved survival	Increased arrhythmogenicity

MBTS or RVPAS at the time of a Norwood procedure. Of note, the SVR trial was the first randomized control trial comparing two operations in congenital heart surgery. The primary outcome was transplant-free survival at 12 months, which was statistically better at 74% for the RVPAS as compared to 64% for the MBTS. Secondary outcomes were perioperative morbidity after the Norwood procedure, unintended cardiovascular interventional procedures, right ventricular function by echocardiography, pulmonary arterial size by angiography, and neurodevelopment at 14 months [44].

The longer-term results at both 3 and 6 years have now also been reported. At 3 years, transplant-free survival was not statistically different at 67% for RVPAS as compared to 61% for the MBTS. The RVPAS group had more catheter interventions and worse RV ejection fraction [45]. At 6 years, transplant-free survival was not statistically different at 64% for RVPAS as compared to 59% for the MBTS. The RVPAS group had more catheter interventions pre-Fontan, and there was no difference in either RV ejection fraction or complications between the two groups. However, there was overall significant morbidity in both groups [46]. In addition to these results, the SVR database has led to a plethora of other important PHN studies as well [47].

Despite this landmark trial, the controversy regarding shunt type still exists. The initial survival benefit of the RVPAS has statistically been lost in longer-term studies; however, the trend still is present. Overall survival for patients with HLHS needs to improve, and continued investigation into ideal shunt type at the Norwood procedure remains an important clinical question.

## Deep Hypothermic Circulatory Arrest Versus Regional Cerebral Perfusion

Cardiopulmonary bypass technique during the Norwood procedure differs between surgeons and institutions, particularly pertaining to aortic arch reconstruction. Options performed include standard cardiopulmonary bypass with variable degrees of systemic cooling, deep hypothermic circulatory arrest (DHCA), regional cerebral perfusion (RCP), or maintenance of total body perfusion. In general, there is a 50% metabolic reduction for every 10° Fahrenheit (7 °C) decrease in temperature, known as the metabolic reduction Q10 rule. Cooling the patient allows decreased cardiopulmonary bypass flow and systemic oxygen delivery with end-organ preservation. For DHCA, the head is placed in ice, and the patient is cooled to 18 °C for at least 20 min to ensure even cooling. The pump is then turned off and the patient exsanguinated into the venous reservoir for the period of aortic arch reconstruction. This is our preference. In contrast, RCP can be performed by retrograde flow through the superior vena cava (SVC) or antegrade into the head vessels, typically the innominate artery, either by direct cannulation or through a graft. This can be performed during DHCA to maintain continuous cerebral perfusion. A few groups have also described perfusing the brain using the above RCP techniques, as well as the lower body by cannulating the descending aorta.

The Boston Circulatory Arrest Study was a single-center randomized control trial that evaluated perioperative neurologic effects associated with DHCA versus low-flow cardiopulmonary bypass during the arterial switch operation for transposition of the great arteries. This demon-

strated higher risk of clinical seizures, higher risk of ictal activity on EEG monitoring, and greater release of creatine kinase brain isoenzyme associated with DHCA [48]. Long-term neurodevelopmental outcomes at 4 and 8 years of age were then evaluated. At 4 years of age, there was no difference in IQ or overall neurologic status; however, DHCA patients had worse motor coordination and planning [49]. At 8 years of age, both groups were associated with increased risk of neurodevelopmental abnormalities; however, the DHCA patients generally had greater functional deficits [50].

The University of Michigan then conducted a single-center randomized control trial that evaluated neurodevelopment outcomes associated with DHCA versus RCP in patients undergoing the Norwood procedure. Neurodevelopment was measured prior to second-stage palliation and at 1 year of age. This study did not suggest improved outcomes with RCP [51]. At this time, both strategies will continue to be used until further multicenter studies show clear consensus on which technique is related to superior outcomes.

### Delayed Sternal Closure

Delayed sternal closure refers to temporary patch closure of the skin with the sternum left open at the time of the Norwood procedure and other complex congenital heart surgeries. The sternum is then closed as a separate operation typically several days later either in the intensive care unit or operating room. The proposed advantage is to provide more space in the setting of decreased function, myocardial edema, and coagulopathy. This can minimize the effects of diastolic dysfunction and elevated filling pressures, potential compression of anterior structures such as the RVPAS, increased vasoactive requirements with hemodynamic instability, tamponade physiology, and cardiac arrest. The proposed disadvantages are infectious and wound healing risks, need for an additional operation and anesthesia, and prolonged mechanical ventilation. A study using the STS CHSD evaluated 1283 infants undergoing the Norwood procedure from 45 centers. It dem-

onstrated practice pattern variation with regard to delayed sternal closure and that centers with greater use had higher postoperative infection and length of stay [52]. Some institutions and surgeons choose to electively leave all patients open, whereas others selectively decide based on individual patient factors (Table 7.2). Our preference is the latter based on an intraoperative decision by the surgeon.

#### Patient Scenario

*A hybrid Norwood procedure was recommended given the size, age, and presentation of the patient. Once the patient was stabilized with end-organ recovery, he was taken to the operating room for this procedure performed jointly by a congenital heart surgeon and interventional cardiologist. A median sternotomy was performed. Bilateral PA bands were constructed from 3.0 millimeter Gore-Tex graft and applied. Catheter-based distal PA pressures of approximately 15 mmHg were achieved. An angiogram was then performed to assess ductal and arch anatomy. A PDA stent was placed with a completion angiogram performed. The chest was closed and the patient transferred to a dedicated pediatric cardiothoracic intensive care unit.*

### Hybrid Norwood

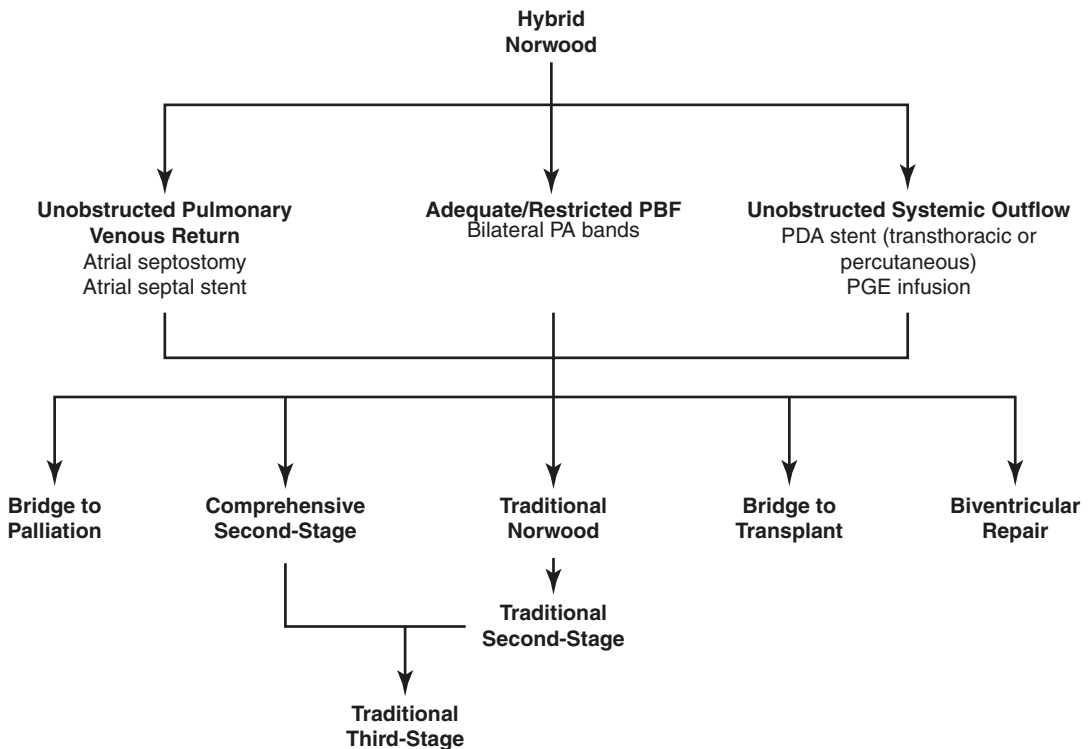
Given the significant morbidity and mortality associated with the Norwood procedure, collaboration between surgeons and interventional cardiologists led to a less invasive alternative strategy first described by Gibbs et al. in 1993 [53]. It has since been advanced by teams in Giessen, Germany, and Columbus, Ohio. This hybrid Norwood procedure, also known as hybrid stage I palliation, has become an evolving therapy in the armamentarium for repair of HLHS.

The hybrid Norwood procedure achieves the same goals of the traditional Norwood procedure

without cardiopulmonary bypass (Table 7.3). Unobstructed pulmonary venous return is achieved by balloon atrial septostomy or atrial septal stent placement. Unobstructed systemic outflow is accomplished by placement of a patent ductus arteriosus (PDA) stent, either percutaneous or transthoracic via the main pulmonary artery, or by continuous prostaglandin infusion. Adequate, but restricted, pulmonary blood flow is achieved by placement of bilateral PA bands. Despite the same goals, multiple strategies have been employed to achieve this result (Fig. 7.3). The Giessen technique is a median sternotomy for placement of bilateral PA bands followed by percutaneous PDA stent placement and atrial septal intervention [54]. The Columbus technique is a median sternotomy for placement of bilateral PA bands and transthoracic PDA stent placement followed by delayed percutaneous atrial septal intervention, except in cases of restrictive or intact atrial septum [55]. An additional technique described is placement of a reversed MBTS to

ensure coronary perfusion in HLHS patients with aortic atresia [56].

The surgical indications for the hybrid Norwood procedure are also quite variable. Some centers have adopted this for all HLHS patients, and others have selectively used it only for high-risk subgroups. Our preference to date has been the latter. High-risk patients are defined as less than 2.5 kg [57], less than 34 weeks gestation, intact or highly restrictive atrial septum, severe tricuspid regurgitation, severe right ventricular dysfunction, severe noncardiac medical or genetic conditions, renal dysfunction, intracranial hemorrhage or neurologic injury, contraindication to cardiopulmonary bypass, severe ascending aortic hypoplasia (<2 millimeters), coronary sinusoids (mitral stenosis, aortic atresia), and postnatal cardiac arrest or shock. Of note, the hybrid Norwood has also been used for potential biventricular patients with Shone’s complex and high-risk features, interrupted aortic arch with high-risk features, and critical aortic



**Fig. 7.3** Hybrid Norwood treatment algorithms and subsequent pathway options



stenosis with poor left ventricular function. The main contraindication to a hybrid Norwood procedure is unfavorable aortic arch and ductal anatomy for PDA stent placement with concern for reverse coarctation, especially in the setting of aortic atresia.

Once the hybrid Norwood procedure has been performed, the subsequent treatment pathway is also controversial (Fig. 7.3). Options include bridge to palliation, comprehensive second-stage traditional Norwood, bridge to transplant, or biventricular repair for non-HLHS patients. Our preference for suitable candidates has been to proceed with a traditional Norwood procedure at approximately 8–12 weeks of age followed by routine staged Fontan palliation. Comprehensive second-stage palliation consists of removal of bilateral PA bands with possible PA augmentation, removal of the PDA stent, the traditional Norwood procedure without the systemic-to-pulmonary artery shunt, and a superior cavopulmonary connection. Both the Giessen and Columbus groups have instead favored this approach. The Giessen single-center 15-year experience of 154 patients with HLHS or variants has been reported. The hybrid Norwood procedure was used for 107 patients, 33 with biventricular repair, 7 with heart transplantation, and 7 with comfort care. Eighty-nine patients went on to comprehensive second-stage palliation. Mortality for first stage was 1.2%, interstage 6.7%, and comprehensive second stage 9%. Overall unadjusted 1- and 15-year survival for all patients was 84% and 77%, respectively [54].

Using the STS CHSD, the outcomes following comprehensive second-stage palliation were reviewed. It consisted of 209 patients, 68% with HLHS, from 49 centers between 2010 and 2016. Overall operative mortality was 12.4%, postoperative major complications occurred in 26.8%, and postoperative ECMO was utilized in 8.1%. Of note, 81 procedures were performed at one institution with most centers only performing 1–2 procedures [58]. Although the results are discouraging, no definitive conclusions can be made. Unfortunately, given the infancy of this treatment and variable practice patterns, the scarcity of published results have yet to define a best practice.

### Patient Scenario

*Postoperative management consisted of balancing the circulation. The patient initially had high oxygen saturations with increasing lactic acidosis. The  $FiO_2$  was therefore decreased to 21% and milrinone infusion initiated. Heparin infusion was begun for the PDA stent. The patient was extubated 2 days later and eventually transferred to the floor. He was discharged after approximately 1 month with nasoenteral feeds, aspirin, furosemide, and digoxin. Extensive counseling was performed with the family prior to discharge, and the patient was entered into the interstage program.*

*He then underwent a traditional Norwood procedure at approximately 8 weeks of age. The operation consisted of an atrial septectomy, connecting the dominant right ventricle to the systemic circulation, removal of the PDA stent, aortic arch reconstruction using pulmonary allograft patch under DHCA without RCP, an RVPAS using a 6-millimeter-ringed Gore-Tex tube graft, and removal of bilateral PA bands without PA augmentation. The sternum was left open and the skin sutured to a temporary patch.*

*The patient had hemodynamic instability and volume overload which improved after several days. Delayed sternal closure was then performed followed by extubation 2 days later. The remainder of the course was unremarkable and followed that of the hybrid Norwood hospitalization described above.*

### Postoperative Management

The postoperative management following either a traditional or hybrid Norwood procedure mandates a thorough understanding of the pathophysiology regardless of the strategy followed at each institution. The goals are to maintain acceptable total cardiac output and balance PBF and SBF to

maintain adequate systemic oxygen delivery. This is assessed by clinical exam, routine vital signs, intracardiac pressure monitoring, continuous mixed venous oximetry, near-infrared spectroscopy (NIRS), continuous pulse oximetry, arterial and venous blood gas sampling, and markers of end-organ function. Typically, the goal is a mean arterial blood pressure approximately 40–45 mmHg, an oxygen saturation 70–75%, an arteriovenous difference of 20%, normal pH, a  $PCO_2$  40 mmHg, a  $PO_2$  30–40 mmHg, normal lactic acid levels without significant base deficit, and a hematocrit greater than 40%. To achieve this physiologic balance, the systemic (SVR) and pulmonary vascular resistance (PVR) can be manipulated to control respective blood flows. The SVR can be increased by systemic vasoconstrictors such as vasopressin, norepinephrine, epinephrine, or high-dose dopamine infusions. The SVR can be decreased by systemic vasodilators such as milrinone, direct arterial vasodilators, or alpha-antagonists. The PVR can be increased by increasing  $PCO_2$ , either through decreased minute ventilation or addition of inhaled  $CO_2$ , or decreasing  $PO_2$ , either by lowering the  $FiO_2$  and PEEP or administration of sub-ambient  $O_2$ . The PVR can be decreased by decreasing  $PCO_2$ , increasing  $PO_2$ , or adding pulmonary vasodilators such as inhaled nitric oxide or oral sildenafil. In addition, optimization of medical therapy is important with temperature control, appropriate pain and sedation control, possible neuromuscular blockade, inotropic support, acid-base management, and adequate oxygen carrying capacity with blood transfusion as needed. In general, the goal for the balance between SBF and PBF is generally a ratio of 1:1, which maintains both adequate peripheral oxygen saturation (~75%) and systemic cardiac output.

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## Second-Stage Palliation

This stage is typically performed between 4 and 6 months of age. Once deemed an appropriate candidate, the options include the hemi-Fontan

or bidirectional Glenn procedure (Fig. 7.2). Both create a superior cavopulmonary connection as the source of pulmonary blood flow while volume unloading the ventricle. The previous systemic-to-pulmonary artery shunt is removed.

The bidirectional Glenn procedure creates this connection by an end-to-side anastomosis between the divided SVC and a longitudinal ipsilateral branch pulmonary arteriotomy. In contrast, both the original and modified hemi-Fontan procedures create this connection by suturing a right atriotomy to the central pulmonary arteries which are augmented with an allograft patch. The right atrium, which is now a common atrium due to the previous atrial septectomy, is partitioned by patch. Therefore, the SVC return enters the partitioned superior portion of the common atrium to flow into the pulmonary arteries. The inferior vena cava (IVC) return enters the partitioned inferior portion of the common atrium to enter the right ventricle [59, 60].

There remains controversy as to the appropriate second-stage palliation. Excellent results have been demonstrated with both procedures. The choice becomes institution and surgeon dependent largely based on experience. The bidirectional Glenn procedure is currently the more commonly performed second-stage palliation at most centers. Advocates favor this approach for the technical ease and ability to perform without cardiac arrest or even without cardiopulmonary bypass [61, 62]. However, the hemi-Fontan is our procedure of choice at the University of Michigan unless anatomically not feasible, such as some cases of anomalous pulmonary venous connections, select cases of abnormal relationship and position of the atria to the ventricles, and some forms of heterotaxy with anomalous systemic venous connections. If bilateral SVC is present, we elect to perform a right modified hemi-Fontan with a left bidirectional Glenn procedure. Although technically more challenging, it is favored because it is felt for many reasons to make patients more suitable Fontan candidates [59]. Optimal PA anatomy is ensured through

routine augmentation of the branch pulmonary arteries. This more complex operation simplifies the lateral tunnel Fontan when the postoperative hemodynamics are more demanding. The entire cardiac output, with the exception of a fenestration, passes through the lungs at the Fontan stage. Therefore, longer anesthetic and cardiopulmonary bypass times can negatively impact the lungs which more seriously affect a Fontan patient. Lastly, mathematical modeling has demonstrated that the hemi-Fontan with lateral tunnel Fontan circulation has more favorable flow patterns with less energy loss and more equal distribution of IVC blood flow, as compared to the bidirectional Glenn with extracardiac conduit Fontan circulation [63].

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### Third-Stage Palliation

This stage is typically performed between 18 and 48 months of age depending on the type of Fontan performed. Once deemed an appropriate candidate, the options include the intra-atrial lateral tunnel Fontan, otherwise known as the lateral tunnel Fontan, the extracardiac conduit Fontan, or the intra-/extracardiac conduit Fontan (Fig. 7.2). Each completes the Fontan circulation by directing the IVC blood directly to the lungs. Following this stage, the entire deoxygenated systemic venous return will drain directly into the pulmonary arteries, driven only by central venous pressure. The oxygenated pulmonary venous return drains into the common atrium to be delivered to the systemic circulation via the systemic right ventricle.

The extracardiac conduit Fontan is performed by placement of an interposition graft, typically an 18–20 mm stretch PTFE graft, between the divided IVC and either the SVC or an arteriotomy on the inferior aspect of the PA involved in the bidirectional Glenn anastomosis. There is controversy though as to the ideal size of the conduit [64] and location of the latter anastomosis [65]. The intra-/extracardiac conduit Fontan is a modification of this where an anastomosis is performed between the end of the conduit and

the atrium surrounding the orifice of the IVC and any additional hepatic veins. The conduit is then brought through the atriotomy which is closed around the conduit. The completion of the conduit is then performed in a similar fashion to the extracardiac conduit described above [66, 67].

In contrast, the lateral tunnel is performed through a right atriotomy from the inferior cavoatrial junction to just inferior to the previously placed hemi-Fontan patch (which is later removed). A lateral tunnel the width of the IVC is created with a PTFE patch. The patch is sutured around the internal orifice of the IVC, anterior to the right pulmonary veins, around the orifice of the SVC, and the anterior edge of the patch is then incorporated into the atriotomy closure. This creates a lateral tunnel pathway within the common atrium where SVC and IVC return is directed into the pulmonary arteries [59, 60, 68, 69].

There also remains controversy as to the appropriate third-stage palliation. Excellent results have been demonstrated with both procedures [70–82]. Once again, the choice becomes institution and surgeon dependent largely based on experience. The extracardiac conduit Fontan is currently the more commonly performed third-stage palliation. Advocates favor this approach for technical ease, ability to perform without cardiac arrest or even cardiopulmonary bypass [71, 83, 84], decreased arrhythmogenicity due to less atrial suture lines and the atrium excluded from higher venous pressures [67, 85], and less PA reconstruction if transplantation required in the future [86].

However, the lateral tunnel Fontan is our procedure of choice at the University of Michigan when anatomically possible for several reasons. The procedure is performed with technical ease following the hemi-Fontan procedure. There are more favorable flow patterns as described above [63]. Less prosthetic material is used which preserves growth potential and possibly decreases thrombogenicity [69]. Fenestration is easily performed, and more ready percutaneous catheter access to the common atrium is maintained. In

addition, a large study from the STS CHSD of 2,747 subjects undergoing the Fontan operation from 2000 to 2009 (lateral tunnel 47%, extracardiac 63%) demonstrated superior early outcomes for the lateral tunnel Fontan. After adjustments for patient factors, a multivariable analysis demonstrated that several factors, including the use of an extracardiac conduit Fontan, were associated with a significantly higher incidence of takedown/revision, Fontan failure, and longer length of stay [80].

Lastly, advocates of the intra-/extracardiac conduit Fontan favor this approach because it offers the advantages of both of the other techniques [67]. However, it is the least commonly performed technique at this time.

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### Role of a Fenestration

With each of these options, one must decide on a fenestration. This is a communication between the Fontan pathway and the common atrium which can be created using a variety of techniques [86–90]. It can be thought of similar to an atrial septal defect in a normal heart. Without a fenestration, an increased transpulmonary gradient could lead to decreased cardiac output, cardiogenic shock, and a failed Fontan circulation. The advantage is to lower Fontan pressures and increase overall systemic oxygen delivery by maintaining cardiac output through right-to-left shunting, particularly in the initial postoperative period. The disadvantages are right-to-left shunting with decreased oxygen saturations, risk of paradoxical emboli, and potential need for fenestration closure [87]. Early on, it was routinely used by many centers. However, as the extracardiac conduit Fontan has become more common, fenestrations with this technique are more challenging to create and less durable. This has prompted these centers to selectively fenestrate only high-risk candidates with successful results [87, 91]. Our preference continues to be routine fenestration of all Fontan patients, albeit with a very small fenestration (2.8–3.0 mm), which generally closes spontaneously after the postoperative period.

#### Patient Scenario

*The patient then underwent a hemi-Fontan procedure at 6 months of age followed by a lateral tunnel Fontan procedure with a 3 mm fenestration at 2 years of age. The patient has done well and is being evaluated in a neurodevelopmental clinic and followed by his referring cardiologist at an outside hospital. He has no evidence of a failing Fontan circulation at this time.*

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### Mechanical Circulatory Support

Mechanical circulatory support, both short and long-term, is challenging in patients with HLHS at various stages of palliation. The anatomy and surgical reconstructions are complex. In addition, many of these patients have limited vascular access given their extensive hospitalizations and repeat catheterizations.

Extracorporeal membrane oxygenation (ECMO) is the mainstay of short-term support. It is tailored to patient factors and the stage of palliation. As a general rule, femoral cannulation is not considered in patients less than 15 kg at our institution. Pre-first-stage HLHS patients are very difficult to support through peripheral cannulation. As a result, some centers will not offer ECMO at this stage. First-stage patients have multiple options, either transthoracic or peripheral cannulation, depending on the time from surgery and surgeon preference. Second-stage patients are also difficult to support. Cannulation of both the superior cavopulmonary pathway and the common atrium is recommended. Failure to decompress the SVC can lead to decreased cerebral perfusion and higher risk of neurologic injury. Third-stage patients also have multiple options, either transthoracic or peripheral, again dependent on multiple factors. For transthoracic cannulation, the surgeon can cannulate either the lateral tunnel or extracardiac conduit instead of the common atrium.

In general, ECMO portends a poor prognosis in HLHS and other single ventricle patients. A

retrospective review of 20 patients with a cavopulmonary connection requiring ECMO reported 55% of patients having known vessel occlusion complicating cannulation options, a 25% incidence of severe neurologic injury, and 30% survival at 35-month follow up [92]. A retrospective review from the Extracorporeal Life Support Organization (ELSO) of 230 Fontan patients requiring ECMO demonstrated only a 35% survival to hospital discharge [93]. A retrospective review of HLHS patients requiring ECMO after the Norwood procedure between 2001 and 2010 at the University of Michigan demonstrated 43.8% survival to hospital discharge, 35.9% survival to second-stage palliation, and only 25.4% survival to third-stage palliation [94].

Long-term support unfortunately lacks an ideal device at this time. There is active investigation into cavopulmonary assist, such as a viscous impeller pump [95] or systemic ventricular assist device [96]. Case reports have been published using the Berlin Heart [97, 98], and other devices are also being considered. As this area evolves, hopefully more established treatments will develop. Regarding patients with failing Fontan physiology, there is a serious need for transplantable hearts with limited donor availability.

## Transplantation

Heart transplantation was considered early on as primary treatment for HLHS [7, 8]. However, due to limited donor availability and advancements made in staged palliation, it is less commonly utilized. For example, children in need of heart transplantation have the highest solid organ waitlist mortality [99]. Despite this, it does play a role at each stage. The current indications in HLHS are primary transplantation if poor RV function, candidates unable to proceed to the next stage of palliation or with poor right ventricular function and/or tricuspid regurgitation, and those with sequelae of a failed Fontan circulation [21], of who will likely comprise the largest need in the future.

## Conclusion

The most common severe form of congenital heart disease is HLHS. Current traditional surgical management of HLHS consists of staged palliation to a Fontan circulation. Based on this standard management, outcomes have dramatically improved. However, despite these advances, there is still significant morbidity and mortality associated with HLHS. This has led to investigation into new and alternative therapies. As a result, multiple controversies exist for the surgical management of HLHS. Advancements in understanding and continued collaboration will be paramount to establish best practices and resolve these current controversies. The hope is this will translate to continued improvement in outcomes for this challenging group of patients.

### Take-Home Points

- Current traditional surgical management of HLHS consists of the Norwood procedure at birth, second-stage superior cavopulmonary connection at typically 4–6 months of age, and a completion Fontan procedure at 18–48 months of age.
- Current controversies include regionalization of care to centers of excellence, the role of fetal cardiac intervention, appropriate management at each stage of palliation, and the role of mechanical circulatory support and transplantation.
- Controversies in first-stage palliation with the Norwood procedure include the appropriate shunt type, use of deep hypothermic circulatory arrest or regional cerebral perfusion, need for delayed sternal closure, differences in postoperative management, and the evolving role of the hybrid Norwood procedure.



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