A Novel Method to Safely De-Air a HeartWare System in a Single-Ventricle Patient by Utilizing ECMO and a Minimized CPB Circuit

Tiffany M. Robb, MS, CCP, LP, CPBMS; Blake Denison, MSHCT, CCP, LP, FPP; Michelle Mizrahi, MD; Richard Owens, BS-MT, CCP, LP, FPP; Charles D. Fraser Jr, MD

Department of Surgery and Perioperative Care and Pediatrics, The University of Texas at Austin Dell Medical School, Austin, Texas; and The Texas Center for Pediatric and Congenital Heart Disease, Dell Children’s Medical Center, Austin, Texas

This paper was presented orally by the first author at the AmSECT 59th International Conference—A Virtual Experience (May 1–4, 2021) and the Texas Heart Institute 2021 Perfusion Conference Virtual Symposium (June 4–5, 2021).

Abstract: The survival of congenital heart disease (CHD) patients with single-ventricle (SV) physiology has markedly increased as a result of advances in operative techniques and postsurgical management. Nonetheless, these patients remain highly susceptible to end-stage heart failure requiring cardiac replacement therapies at early ages. Given a worldwide shortage of transplantable organs, mechanical circulatory support (MCS) represents an alternative treatment option. The significant heterogeneity of the SV population presents unique indications for MCS that have begun to be evaluated. This case study describes a 12-year-old female with heterotaxy syndrome and an SV condition, previously palliated with a Fontan operation at another institution. The patient was placed on veno-arterial (VA) extracorporeal membrane oxygenation (ECMO) during prolonged cardiopulmonary resuscitation, and later underwent HeartWare ventricular assist device (HVAD) implantation as a bridge to transplantation (BTT). A novel method was chosen to optimize careful de-airing of the heart through a minimized cardiopulmonary bypass (CPB) setup, during full ECMO support and surgical insertion of the HeartWare. The ascending aorta was vented proximal to the HVAD outflow graft anastomosis through a minimized CPB circuit at <10% of the ECMO flow rate. This circuit adaption allowed for euvolemic resuscitation via connection from the minimized CPB circuit to the venous limb of the ECMO circuit. The transition from VA-ECMO to the HeartWare was well tolerated despite a challenging sternotomy and cardiac anomaly. A minimized bypass circuit proved efficacious for the benefit of volume resuscitation and safe de-airing of the HVAD while on ECMO support. The literature is limited concerning safe practices for implantation of durable VADs in complex SV patients coupled with those transitioning from varying modalities of MCS. As SV survivability regresses to heart failure, it is essential that we share techniques that aim to improve the long-term outcomes for successful BTT or bridge to decision (BTD). Keywords: cardiopulmonary bypass, congenital heart disease, extracorporeal membrane oxygenation, left ventricular assist device, heart failure, HeartWare, single ventricle.

Advancements in surgical technique and medical care have led to improved outcomes and increased survival of congenital heart disease (CHD) patients with single-ventricle (SV) physiology (1). With more than 1,000 new Fontan operations performed annually in the United States and Canada, the first generation of surviving patients who have reached the Fontan stage are now well into adulthood (1). Despite successful staged palliation attempts, long-term complications and the potential development of heart failure challenge the overall survivability of this patient population. At current, survival to hospital discharge is 30–50% when considering the cumulative subset of patients with single-ventricular anatomy and physiology who require mechanical circulatory support (MCS) (1,2). In a multi-institutional review of more
than 750 children supported on extracorporeal membrane oxygenation (ECMO) as a bridge to transplant (BTT), 30% were SV with the poorest results for death on the waiting list (48%), death while on ECMO (45%), and death after transplant and before discharge (69%) (2). In contrast, outcomes for all children receiving a ventricular assist device (VAD) as the bridge modality fare significantly better (2,3). This excludes the neonatal SV cohort with a systemic source of pulmonary blood flow, where the survivability of VAD versus ECMO support is unclear following a stage I palliation or Norwood procedure (2,3).

The increased number of patients undergoing Fontan palliation and the inevitable failure of this circulation alternative, adds additional weight to the constant shortage of cardiac allografts for transplantation (4). Consequently, heart failure in the SV population has become the most common indication for heart transplantation in children (1). In this setting, MCS can be used as an alternative management option for cardiac failure in several varying modalities (5). ECMO has been widely used as an MCS technique because of its speed of initiation, efficiency toward myocardial recovery, and ability to support the cardiac and pulmonary circulations of patients of any size (1). However, as MCS practices evolve, the significant long-term risk profile of ECMO best indicates its use as a bridge to VAD and/or a bridge to decision (BTD). In comparison to ECMO, a VAD offers the benefits of longer duration of support and should be considered an exclusive therapy. Current transplant allocation in pediatrics places children with VADs at top priority (Status 1A) (6). Nevertheless, the routine use of VADs in the pediatric population is limited to the mismatch between device options and patient body size (7).

Here we present an original technique for the implantation of a durable VAD, which combines ECMO and a minimized cardiopulmonary bypass (CPB) circuit in a patient suffering from complex single-ventricle CHD. The HeartWare® ventricular assist system (HVAD®) (Medtronic, Minneapolis, MN), as further referenced in this case study is a small (displaced volume = 50 mL, weight = 160 g), intracorporeal continuous-flow centrifugal pump intended for implantation into the left ventricle and augmentation of cardiac output. In 2012, the HVAD received U.S. Food and Drug Administration (FDA) approval in the adult (≥18 years old) population (6). Even before FDA approval was gained, sporadic cases of pediatric implantations were accomplished despite neither being designed nor prospectively tested in this population (6). Although little data exists surrounding the safety and efficacy of the HeartWare in the pediatric population, outcomes of this device in children have been published in the form of case reports, case series, single-center experiences, and a worldwide survey conducted by Conway et al. (6,8–15). Among the 498 children enrolled between 2012 and 2017 in Pedimacs, the mechanically assisted circulatory support event-driven registry, 41% received HVADs as their first device implanted (6). At the time of implantation, 12 of these children who were 58.3% more likely to have a primary diagnosis of CHD, weighed <20 kg with a body surface area (BSA) of 0.7 ± 0.1 m², mean weight of 16.7 ± 2.5 kg, and age of 5.6 ± 2.5 years (6). In the overall study population, the median age, BSA and weight of these children was 14.4 years, 1.5 m², and 51.5 kg, correspondingly (6). The first successful long-term application of the HeartWare in an 11-year-old (BSA 1.1 m²) with a hypoplastic left heart and failed Fontan circulation was reported in 2014 (16). Preceding recent actions that discontinued the HVAD, this flagship product was routinely selected as the device of choice in larger children with end-stage heart failure (6). In total, this device has represented a favorable selection for pediatric MCS owing to its integrated short inflow cannula, complete intrapericardial implantation, percutaneous driveline, and capacity for outpatient management (5). In this case, the HVAD was elected for implantation per surgeon in support of the patient-compatible pump size, ability for hospital discharge to home, a durable means for bridge to transplantation, and general experience with this device in the pediatric populace.

**DESCRIPTION**

This case report details a 12-year-old female with heterotaxy syndrome and failing SV physiology, who underwent HVAD placement while awaiting a heart transplant. At the time of her VAD operation, the patient (11 years and 9 months of age) weighed 31.4 kg and measured 142 cm in height with a BSA of 1.1 m². The patient encountered bilateral Glenn and fenestrated Fontan operations at 1 and 3 years of age, respectively, as staged palliation attempts for an unbalanced atrioventricular septal defect. At the age of 11, she suffered from acute decline in her exercise tolerance and was admitted for inpatient diagnostic evaluation. A thrombus was discovered in her Fontan circuit and enoxaparin, a low molecular weight heparin, was administered subcutaneously for thromboprophylaxis. While hospitalized, the patient suffered from a sudden event of atrial tachycardia that degenerated into pulseless ventricular tachycardia. She was emergently intubated and cardiopulmonary resuscitation (CPR) was initiated. Chest compressions continued for 110 minutes, until she was cannulated and placed on veno-arterial (VA) ECMO. Failure to wean from VA-ECMO and elevated Fontan pressures of approximately 20 mmHg prompted the decision for implantation of a durable VAD as a BTT. Leading up to HVAD placement the.
patient remained on VA-ECMO for 6 days via right neck cannulation through the common carotid artery and internal jugular vein, at a flow rate of approximately 80 mL/kg/min. During this time, the patient received a continuous intravenous infusion of unfractionated heparin with targeted therapeutic ECMO anticoagulation defined by anticoagulation time (ACT) range 160–180 seconds and anti-Factor Xa activity levels (anti-Xa) between .3 and .7 IU/mL. This heparin infusion was safely weaned in accordance with our institution’s protocol prior to the patient’s scheduled VAD implantation to minimize the potential intraoperative bleeding risk.

In anticipation of transitioning from ECMO to CPB support in the operating room, a complete CPB circuit setup was prepared on a LivaNova Heart-Lung Machine S5 (LivaNova, Houston, TX) with a physiologic blood prime. The disposable CPB equipment was chosen per Dell Children’s Medical Center CPB guidelines. The target CPB flow rate of 2.67 L/min was calculated at a cardiac index of 2.4 m²/min, or equivalent to 85 mL/kg/min. To match the flow requirements with an appropriate CPB circuit size, a CAPIOX® RX15 (Terumo Cardiovascular Systems Corporation, Ann Arbor, MI) hard-shell venous reservoir plus oxygenator and a 3/8-inch arterial by 3/8-inch venous roller pump circuit were arranged. The crystalloid circuit prime constituents included 700 mL Plasma-Lyte A (Baxter Healthcare Corporation, Deerfield, IL) and 350 mL .45% sodium chloride (half normal saline) (Hospira, Inc., Lake Forest, IL), with the addition of 4,000 IU heparin (1,000 IU/mL) for the safe management of extracorporeal anticoagulation. Two units of banked blood group compatible red blood cells (609 mL, total) and one unit of thawed plasma (297 mL) were added to further optimize the prime hematocrit and colloid osmotic pressure. The CPB prime was then circulated at 37°C at a fraction of inspired oxygen of 21% and sweep gas rate of .85 L/min, with the balanced titration of .05 L/min of carbon dioxide. Prebypass ultrafiltration (PBUF) was initiated to counter the effect of hemodilution and reduce the total circuit prime to 1,000 mL. A total of 19 mEq of 8.4% sodium bicarbonate (1 mEq/mL) and 450 mg calcium chloride (100 mg/mL) were further required to buffer the pH and electrolyte composition of the prime. The following circuit prime gas was drawn and accepted as physiologic, using a Siemens RAPIDPoint® 500 (Siemens Medical Solutions USA, Inc., Malvern, PA) blood analyzer: pH, 7.39; PaCO$_2$, 37 mmHg; PaO$_2$, 141 mmHg; base deficit, −2.3 mmol/L; lactate, 3.0 mmol/L; sodium, 147 mmol/L; potassium, 4.05 mmol/L; ionized calcium, 1.32 mmol/L; chloride, 99 mmol/L; glucose, 136 mg/dL; and hematocrit of 31%.

The patient was transported to the operating room on ECMO support. A repeat median sternotomy was performed with great difficulty owing to the patient’s existing hemorrhagic lesions and fractured sternum, secondary to prolonged CPR efforts performed the week prior. The plan to transition from ECMO to full CPB was aborted because of the complexity of adhesions from multiple mediastinal reoperations. Despite optimal intraoperative VA-ECMO support, the absence of an open venous reservoir and accompanying CPB circuit presented a unique challenge to safely de-air the outflow graft of the HVAD system while preserving normovolemia (Figure 1A). After a brief deliberation of safe solutions, a novel extracorporeal method was determined.

The operative procedure was adapted as follows while the patient remained on full VA-ECMO support at a flow rate of 80 mL/kg/min (Figure 1). The HVAD was prepared at the surgical field. The patient was given a 400 IU/kg intravenous dose of unfractionated heparin resulting in an appropriate ACT of 497 seconds. Given the patient’s SV physiology and lateral position of the heart apex, apical cannulation of the HeartWare pump was deemed inadequate. After lengthy consideration, it was elected to place the HeartWare device in the right common atrium. A boring tool was used to create an opening in the atrium where the HeartWare device was sutured into place without difficulty. Owing to the patient’s right aortic arch anatomy, the distance between the device and the ascending aorta was unusually short. Consequently, a side biting clamp was applied to the undersurface of the aortic arch. The VAD outflow graft was trimmed to meet the distance between the HeartWare blood pump and inferior aortic arch. Meanwhile, a minimized extracorporeal resuscitation circuit was assembled in preparation for the de-airing phase of the operation (Figure 1B and C). A high flow stopcock was attached post oxygenator to the 1/4-inch arterial recirculation line from the CPB circuit (Figure 1C). A volume resuscitation line was then attached from the high flow stopcock off the CPB arterial recirculation line to the venous stopcock of the ECMO arterial-venous bridge (Figure 1C). The position of the VAD outflow graft on the undersurface of the aortic arch indicated the conduct of de-airing to be achieved at the highest point of the ascending aorta. To begin de-airing the heart, the surgeon inserted an aortic root needle into the ascending aorta proximal to the HVAD outflow graft insertion site. This created a pathway for purging any gaseous emboli entrained in the ascending aorta through a designated vent to the bypass reservoir. This blood and air mixture was actively pumped into the top of the CPB hard-shell cardiectomy reservoir at a rate of 150 mL/min or less than 10% of the ECMO flow rate (Figure 1B). This blood volume was then pumped at a similar rate through the
oxygenator, followed by the 37 μm ALF and bubble detector of the CPB circuit, before reinfusion in to the venous limb of the ECMO circuit bridge (Figure 1C). Venting and volume replacement were continuously titrated to maintain the hemodynamic stability of the patient during sustained VA-ECMO support. The patient was weaned from ECMO as the HVAD pump was gradually initiated. The aortic root vent was removed once the evacuation of air was deemed a success via visualization with transesophageal echocardiography (TEE). Upon establishing stability of the VAD, ECMO cannulas were withdrawn and the corresponding vessels repaired. Systemic heparin anticoagulation was fully reversed with the administration of protamine to abate intraoperative hemorrhage. After 490 days on HVAD support, the patient underwent successful heart transplantation.

Figure 1. Diagram of a minimized CPB circuit setup for the safe de-airing of the heart following HeartWare HVAD insertion, and reinfusion of vented blood from the aortic root while supported on VA-ECMO. (A) HVAD system. (B) Minimized CPB circuit for venting of the aortic root to the CPB reservoir. (C) Volume resuscitation circuit for reinfusion of filtered and oxygenated blood from the CPB setup directly to the venous limb of the ECMO circuit.
COMMENT

Individuals with SV physiology comprise a heterogeneous and intrinsically difficult subgroup of patients with CHD. As the SV population continues to grow, more refined strategies for the delivery of mechanical circulatory support are necessary. The current outcomes for patients with SV failure requiring MCS at various stages of palliation, are poor and difficult to predict (1). Owing to the drastic alterations of the clinical condition of SV patients over time, the concept of MCS in this group is based on the need to reduce their systemic venous pressure while augmenting cardiac output (5). Therefore, improved timing and patient selection for VAD implantation is critical to the success of MCS as a growing indication for BTT.

There is limited data pertaining to pediatric VAD support specifically in SV patients who have undergone multiple palliative procedures (1–3,5). At present, there is no official standard for the conduct of de-airing the heart during the implantation of the HeartWare ventricular assist system. While the efficacy of the de-airing process is universally evaluated with the use of TEE, the chosen technique for de-airing the heart prior to HVAD initiation depends on the patient’s anatomy and operative status. Few techniques for de-airing the HVAD have been described in the literature (7,17,18). Implantation and de-airing of the HVAD on CPB requires a full loading dose of heparin accompanied by appropriate ACT monitoring >480 seconds. CPB can be indicated in concurrence with VAD implantation specifically for an unstable situation or thrombus excision. De-airing is typically conducted in a controlled fashion via an aortic root vent connected to the heart-lung machine. However, the adverse side effects of CPB pose an existential risk, begging for less invasive off-pump methods. Alternatively, a minimally invasive approach has been described for the implantation of the HVAD via a lateral thoracotomy incision with exposure of the aorta in case of the emergent need for CPB; nevertheless, this approach has been mostly designated for non-redo cases (18). Rapid pacing has also been used to facilitate the application of the punch and insertion of the HVAD pump followed by careful de-airing through an aortic root needle (18). This approach requires reduced anticoagulation with a target ACT >200 seconds (18). A lower target ACT can be beneficial in patients with heparin-induced thrombocytopenia (HIT) requiring substitute anticoagulation. ECMO remains a circulatory support option during the de-airing phase of a durable VAD insertion and can be monitored at a lower ACT. However, the closed-circuit design of this support method alone is unsatisfactory in its ability to deliver rapid early volume replacement and eradicate free air.

In review, this report describes an innovative technique for implanting and safely de-airing the HVAD system on ECMO that has not yet been reported in the literature. Given the challenging nature of this patient’s SV anatomy, our goal was to devise a more controlled, timed, and precise operative procedure for de-airing the heart in conjunction with a physiologic, zero-balance volume resuscitation strategy. The main advantage to this method was achieving continuous euvolemic resuscitation for adequate ventricular filling and a smooth, air-free transition from ECMO to HVAD. Although full bypass anticoagulation was necessary for the brief use of a minimized CPB setup, anticoagulation reversal with protamine and hemodynamic stability were successfully established. Several perfusionists were collectively involved in the careful conduct of the minimized CPB circuit, ECMO wean and initiation of the HVAD system. In short, this case report offers an adjunctive method to scavenge air from the heart during the implantation of a durable VAD on ECMO, when conventional CPB is not a suitable alternative. Although Medtronic has recently halted the sale and distribution of the HeartWare HVAD, the techniques outlined in this report persist in relevance to the current market of durable implantable VADs. Principally, unveiling new techniques for clinical reference and the safe management of complex patients will facilitate the potential for improved outcomes in a growing pediatric MCS population. Sharing practices that advance the likelihood of bridging to individualized therapies is paramount in the complex CHD community, considering that they do not conform to a “one-size-fits-all” approach.

REFERENCES
