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PII: S2666-2507(23)00402-9
DOI: https://doi.org/10.1016/j.xjtc.2023.10.022
Reference: XJTC 1551

To appear in: JTCVS Techniques

Received Date: 5 May 2023
Revised Date: 2 September 2023
Accepted Date: 14 September 2023


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Disclosure statement

CDM, MJO, CWW, JBE, KYL: no relevant financial disclosures
JJE: Supported by NIH K08HL159311
JHB: Supported by NIH K12HD043245
JR: Consultant for Bayer, Merck, Bristol Myers Squibb, AskBio
KM: Surgical Consultant for Berlin Heart, Abbott Laboratories, PECA Labs
Funding statement

Internally funded study

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Word count: 2566
Glossary of Abbreviations

AVVR: atrioventricular valve regurgitation
BNP: b-type natriuretic peptide
CPB: cardiopulmonary bypass
PA: pulmonary artery
PTFE: polytetrafluoroethylene
SV: single ventricle
VAD: ventricular assist device

Keywords: congenital heart disease; single ventricle heart disease; heart failure; staged palliation; ventricular assist device; hybrid procedure; bridge to transplant

Central Picture Legend

Illustration depicting cannulation strategy for hybrid ventricular assist device placement in patients with hypoplastic aortic arches or aortic coarctation, with common atrial inflow cannula and outflow cannula sewn to a chimney graft sewn to the main pulmonary trunk with an additional graft sewn from the outflow graft to the innominate artery. Note the presence of pulmonary artery bands, ductal stenting, and aortic coarctation.

Central Message

Off-pump SV VAD placement is technically feasible and is possible at the time of hybrid stage one palliation with minimal operative morbidity as a bridge to transplant.
Perspective Statement

Single ventricle ventricular assist device can be placed at the time of hybrid stage one palliation without the use of cardiopulmonary bypass. This technique may allow for quicker recovery, less blood product exposure, and less morbidity while providing a stable platform for bridge to transplant in patients who are not candidates for conventional, staged palliation.

Abbreviated Legend for Central Picture

Single ventricle VAD placement during hybrid stage one, performed off pump
Abstract:

Objective: Infants with single ventricle heart (SV) disease and severe atrioventricular valve regurgitation (AVVR) have poor outcomes following conventional staged palliation. As such, ventricular assist device (VAD) placement along with hybrid stage one palliation has been proposed as a bridge to transplant. We present a novel surgical technique for VAD implantation concurrent with hybrid stage one that avoids cardiopulmonary bypass (CPB).

Methods: Retrospective review of our institutional experience.

Results: Three patients (weight range 2.7kg-3.5kg, age range 3-5 days) underwent hybrid stage one with VAD placement, consisting of bilateral 3.5mm expandable polytetrafluoroethylene (PTFE) pulmonary artery (PA) bands, ductal stent, 6mm Berlin Heart outflow cannula onto main pulmonary trunk with 10mm graft, 6mm Berlin Heart outflow cannula onto the RA, and 10mL Berlin heart pump (Berlin Heart NA, The Woodlands, TX, USA). In patients with severe aortic arch hypoplasia or coarctation, a 4mm PTFE graft was sewn from the VAD outflow graft to the innominate artery to protect coronary and cerebral perfusion. Procedures were performed off-bypass with minimal blood products. Patients were extubated on postoperative days 2, 2 and 5. There were no procedural complications. All patients were transferred out of the intensive care unit and demonstrated appropriate weight gain. Anticoagulation strategy was bivalirudin and antiplatelet therapy. Patients were transplanted after 149, 157, and 288 days of support.
Conclusions: Off-pump SV VAD placement is technically feasible and can be done at the time of hybrid stage one palliation with minimal operative morbidity as a bridge to transplant.
Introduction

Despite consistent advances in surgical palliation and medical management of single ventricle congenital heart disease, certain anatomic and physiologic substrates continue to have unacceptably poor outcomes. Controversy exists concerning the optimal treatment strategy for these neonates including those with poor systemic ventricular function and moderate or severe atrioventricular valve regurgitation. Because outcomes following stage one Norwood in these patients are poor, there has been renewed interest in alternative treatment strategies. While primary cardiac transplantation has been offered as a strategy in these cases, current limitations of the donor pool and resulting extended wait times require mechanical circulatory support strategies that can maintain circulation and minimize end organ injury while awaiting cardiac transplantation.

Recently, several groups have described innovative strategies for performing concomitant hybrid stage one palliation with ventricular assist device placement to avoid morbidity and mortality associated with salvage VAD placement following attempted conventional stage one Norwood or hybrid palliation\(^1\)\(^-\)\(^4\). This approach has allowed for successful bridge to transplantation in these high-risk neonates, but optimal surgical strategies are yet unknown. The purpose of this manuscript is to review our institutional experience with a novel cannulation strategy for hybrid VAD placement that avoids the use of cardiopulmonary bypass, minimizes blood usage, and protects against reverse coarctation in high-risk neonates that are poor candidates for conventional staged palliation.

Methods
We conducted a retrospective review of our experience with simultaneous off-pump hybrid VAD placement between June 2021 (our first case) and March 2023. Per institutional standard operating protocol, any retrospective study of fewer than five patients is exempt from IRB review. Therefore, this study was exempt from IRB review. Demographic, procedural, and outcome data were collected from the electronic medical record. Informed consent was not obtained from subjects, as this study is completely de-identified, contains no images that could be linked to patient identifiers, and does not fall under what our institution considers to be research that requires patient level consent to present or publish. Because of the descriptive nature of this study, no statistical tests of significance were performed.

Surgical Methods and Cannulation

All patients underwent bilateral pulmonary artery banding using 3.5mm ExGraft (PECA Labs, Pittsburgh, PA, USA) graft. The use of such an expandable graft as a banding material permits the theoretical possibility of catheter-based PA band adjustment to compensate for somatic growth during long waiting times. In each case, a side biting clamp was applied to the main pulmonary artery, a pulmonary arteriotomy was performed, and a 10mm Gelweave (Terumo Cardiovascular Systems, Elkton, MD, USA) graft was sewn to the main pulmonary trunk. This graft was then backbled and used as the access for ductal stenting. Following ductal stenting, this graft also served as VAD outflow by securing it to a 6mm Berlin Heart outflow cannula. (Berlin Heart NA, The Woodlands, TX, USA) (Figure 1)

In those patients that had coarctation of the aorta or in whom the development of coarctation of the aorta was deemed likely, a 4mm polytetrafluoroethylene (Gore, Flagstaff, AZ, USA) graft was sewn from the Gelweave graft to the innominate artery to protect the cerebral
and coronary circulations (Figure 2) without the use of an isthmal stent. VAD inflow in all cases was performed via direct right atrial canulation using a 6mm Berlin Heart outflow cannula. (Figure 1) A pursestring suture was placed along the lateral aspect of the right atrium, four pledgeted sutures were placed in the four quadrants of the sewing ring and through the four quadrants of the proposed atriotomy. A right atriotomy was performed and the cannula was parachuted down via the pledgeted sutures and advanced into the atrium. The pledgeted sutures were tied down and were run circumferentially for hemostasis. In our first case using this technique, we gave intravenous adenosine (0.3mg/kg) to arrest the heart, optimize cannula position, and avoid entraining of air. We then modified our technique and inserted the atrial cannula directly without arresting the heart. We did not experience any issues with inflow cannula malposition or obstruction. The cannulae were then tunneled, de-aired, and connected to a 10mL Berlin Heart pump to target a VAD index of 5 L/min/m² or greater. All cases were done without the use of cardiopulmonary bypass and with minimal blood product administration. Pump changes were undertaken to treat thrombosis and/or to upsize in the case of somatic growth as needed.

Patient 1

This was a five-day old 2.7kg male born at term with a prenatal diagnosis of hypoplastic left heart syndrome (mitral atresia, aortic stenosis), muscular ventricular septal defect, and severe tricuspid regurgitation. He underwent successful hybrid VAD placement using a brief period of adenosine-induced (0.3 mg/kg) cardiac arrest during atrial cannulation. The arch and atrial septal communication were thought to be adequate at this point and were not addressed. The patient was extubated on post operative day five. The ICU course was complicated by an increasing
gradient across the interatrial septum that prompted balloon atrial septostomy on postoperative day 17 with subsequent improvement. An increasing retrograde coarctation gradient prompted cardiac catheterization and stenting of the aortic isthmus on postoperative day 65 with resulting improvement.

He was discharged from the ICU on postoperative day 71 and remained in the step-down unit until he was transplanted following 157 days of support. He required one Berlin Heart pump exchange on postoperative day 58. He experienced a brief elevation of b-type natriuretic peptide (BNP) levels to 1000 pg/mL during his diagnosis and treatment of coarctation, but otherwise these values and his serum creatinine were within normal limits throughout the duration of support. He was able to grow and feed throughout his time on VAD. Prior to transplant, his class I PRA was 8% and his class II PRA was 0%. His weight at the time of transplant was 5.75kg (1.5th percentile). His intraoperative course was notable for poor aortic tissue quality following removal of the isthmal stent that complicated aortic arch reconstruction. While this did not result in any technical complications or increased graft ischemic time, this experience led us to abandon isthmal stenting in these patients. Post-transplant, he developed graft failure requiring biventricular assist device placement. His condition progressed to multiorgan failure and care was withdrawn 19 days post-transplant.

Patient 2

This was a three-day old 2.8kg male born at term with prenatal diagnosis of heterotaxy (asplenia), unbalanced atrioventricular canal to the right with left ventricular hypoplasia, double-outlet right ventricle, severe atrioventricular valve regurgitation, and ipsilateral pulmonary veins. He underwent successful hybrid VAD placement. The aortic arch and interatrial septum were
deemed adequate and were not addressed. He was then extubated on postoperative day two and had a prolonged but uncomplicated ICU stay of 41 days. He required one Berlin Heart pump exchange on postoperative day 97. Following 149 days of support, he was successfully transplanted. His BNP remained low, and his serum creatinine remained within normal limits. He was able to feed and grow throughout his time on support. Prior to transplant, his class I and II PRA were 0%. His weight at the time of transplant was 6.8kg (11.8th percentile). Post-transplant the patient suffered graft failure requiring ECMO support. His condition progressed to multiorgan failure and refractory hypotension and care was withdrawn 27 days post-transplant.

Patient 3

This was a three-day old 3.5kg male born at term with prenatal diagnosis of severely unbalanced atrioventricular canal to the left with right ventricular hypoplasia, D-transposition of the great vessels, severe left sided atrioventricular valve regurgitation, large anterior malalignment ventricular septal defect, mild ascending arch hypoplasia and discrete coarctation of the aorta. He underwent successful hybrid VAD placement. To address the aortic coarctation, a 4mm polytetrafluoroethylene (Gore, Flagstaff, AZ, USA) side graft was sewn from the VAD outflow graft to the innominate artery prior to initiation of VAD support. The patient was extubated on postoperative day two, and had an uncomplicated ICU course leading to discharge from the ICU on postoperative day 14. He underwent Berlin Heart pump exchange on postoperative days 24, 54, 104 and 170. He suffered a hemorrhagic stroke on postoperative day 205 but has demonstrated good recovery with no obvious residual defects. His BNP remained low, and his serum creatinine remained within normal limits. Following 288 days of support, he was successfully transplanted. He was able to feed and grow throughout his time on support,
achieving a weight of 8.5kg (29.9th percentile) at the time of transplant, and his class I and II PRA were 0%. His post-transplant course was unremarkable. He underwent delayed sternal closure and extubation on postoperative day two, was discharged from the ICU on postoperative day six, and was discharged from the hospital on postoperative day thirteen.

**Discussion**

These cases demonstrate our initial experience with our newly implemented strategy of concomitant off-pump ventricular assist device placement and hybrid stage one palliation in neonates deemed an unacceptably high risk for conventional staged palliation. The advantages of this technique include the avoidance of cardiopulmonary bypass with minimal blood usage and its associated morbidities, ductal stenting through a side graft instead of directly cannulating the main pulmonary artery, the ability to bypass aortic coarctation and equalize flow to systemic, cerebral and coronary circulations, and avoiding the tenuous physiology of conventional staged palliation with high-risk features such as severe AVVR. Additional benefits include the ease with which the VAD outflow graft can be cannulated, or the entire VAD system can be converted, for cardiopulmonary bypass at the time of cardiac transplantation. Furthermore, the use of a bypass graft avoids aortic isthmal stent placement, which can complicate arch reconstruction at the time of cardiac transplant.

Our technique differs from the reported operative strategies primarily in the avoidance of cardiopulmonary bypass. Previous reports have used cardiopulmonary bypass with either cardioplegic or fibrillatory arrest\(^1\)\(^-\)\(^5\). Putative advantages of avoiding cardiopulmonary bypass in these patients include decreased coagulopathy and resulting blood transfusions, decreased pulmonary and renal morbidity and, potentially, decreased ICU-related and postoperative morbidities. Because our experience with hybrid palliation and VAD is relatively new, we are...
not able to make any comparisons between patients who underwent a single stage, off-pump hybrid VAD procedure and those patients who had either sequential hybrid and later VAD placement or those patients who had their hybrid VAD procedures done on cardiopulmonary bypass. As we have gained experience with this technique and in managing these patients our ICU length of stay has decreased, suggesting that there may be a learning curve associated with introducing this surgical strategy. Interestingly, Merritt et al, in a report of their univentricular VAD strategies, state that they initially attempted off-pump VAD placement in these patients, but abandoned this technique after having had issues with VAD inflow\(^2\). We have not encountered any issues with VAD inflow in our current cannulation strategy. Further studies will be needed to determine whether the theoretical advantages of avoiding cardiopulmonary bypass translate into improved outcomes. Our mean duration of ventilation, at 3 days, is shorter than previous reports (7+/−3 days\(^1\)), and ICU length of stay, while heterogeneous, is also considerably less than what has been previously reported\(^3\) suggesting that there may be some benefit in avoiding cardiopulmonary bypass in these patients.

Despite these differences, many aspects of our intraoperative and postoperative care are similar to what has been reported. The use of Berlin Heart outflow cannulae minimizes the interface between the cannula and the atrium, while the interposition graft connected to the outflow cannula allows for unobstructed flow and optimal cannula position away from the midline. Furthermore, as has been described previously\(^1\), our institutional preference is to use bivalirudin for anticoagulation. As other groups have reported, early initiation of mechanical support and avoiding accrual of morbidity and organ dysfunction are key to stabilizing these patients and optimizing their candidacy for transplant\(^1-5\). The VAD support times reflect the unfortunate reality of prolonged waitlist times for neonates, and are similar to what has been
Avoiding small cannulae and small interposition grafts helps to decrease the risk of hemolysis and its associated comorbidities. Notably, we did not have any patients demonstrate significant hemolysis or renal insufficiency during their support time.

The preliminary nature of this study and small patient population challenges interpretation of the post-transplant outcomes. While only one patient survived to discharge, all were nutritionally replete, hemodynamically stable, and mostly unsensitized at the time of transplant. That two still developed profound graft dysfunction is difficult to explain, and reflects both the unique challenges that these children face in transplantation and an incomplete understanding of how best to prevent and manage graft dysfunction in these fragile children. All hybrid VAD patients have risk factors for graft dysfunction, including ventricular assist device at time of transplantation and congenital heart disease. Of note, graft ischemic times for our patients were 286, 200, and 228 minutes. Other groups have published more auspicious transplant outcomes, and we anticipate that our incidence of graft dysfunction in these patients will regress to what has been previously demonstrated.

Improvements in surgical methods have prompted a renewal of interest in early initiation of ventricular assist as a bridge to transplant in high-risk single ventricle neonates. While such improvements have shown considerable promise as a stable platform on which to bridge these high-risk neonates to cardiac transplantation, optimal surgical and treatment methods have yet to be established. Challenges to VAD placement in these patients include higher flows to accommodate single ventricle physiology, somatic growth while awaiting transplantation, the potential for prolonged ICU stay and inability to be discharged home, bleeding that can lead to blood product administration and subsequent immunologic sensitization, and anatomic challenges such as reverse coarctation and the need for durable pulmonary blood flow. Our
strategy of avoiding cardiopulmonary bypass in hybrid stage one palliation with VAD placement attempts to overcome many of the challenges while avoiding the operative complexity and morbidity associated with cardiopulmonary bypass. While the hybrid VAD physiology imparts long term ductal stenting and PA banding that may complicate later cardiac transplant, we have found that the aortic arch and pulmonary artery reconstruction has been technically feasible at the time of transplant. Furthermore, by avoiding the long-term sequelae of valve regurgitation and/or heart failure, patients can arrive at cardiac transplantation without as much end-organ injury. This strategy may not be feasible for all patients, as some patients may require surgical septectomy or other concomitant procedures that require CPB. In select patients, however, this strategy can be performed with acceptable short-term results. Further studies are needed to establish optimal surgical techniques and improve outcomes in this very high-risk group of patients.

Figure Legends

Figure 1. Illustration depicting cannulation strategy for hybrid ventricular assist device placement, with common atrial inflow cannula and outflow cannula sewn to a chimney graft sewn to the main pulmonary trunk. Note the presence of pulmonary artery bands and a ductal stent.

Figure 2. Illustration depicting cannulation strategy for hybrid ventricular assist device placement in patients with hypoplastic aortic arches or aortic coarctation, with common atrial inflow cannula and outflow cannula sewn to a chimney graft sewn to the main pulmonary trunk...
with an additional graft sewn from the outflow graft to the innominate artery. Note the presence of pulmonary artery bands, ductal stent, and aortic coarctation.

Acknowledgement Illustrations were created for this article by Eo Trueblood and Stream Studios, Philadelphia, PA, USA.

References


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May 6, 2023