Chapter

36

Right Ventricular Assist Device

Rajeev Wadia and Jamie McElrath Schwartz

Case Scenario

A 14-year-old male with acute decompensated heart failure secondary to viral myocarditis underwent placement of a HeartWare™ left ventricular assist device. Prior to separation from cardiopulmonary bypass (CPB), transesophageal echocardiography showed moderate right ventricular (RV) dysfunction despite adequate right heart filling, and infusions of milrinone 0.5 mcg/kg/minute and epinephrine 0.03 mcg/kg/minute were initiated, along with inhaled nitric oxide at 20 ppm. As CPB was weaned, echocardiography was utilized to determine optimal HeartWare™ speed by ensuring maintenance of appropriate midline intraventricular septal position and aortic valve closure. After separating from CPB, RV function further declined, and central venous pressures >18 mm Hg were noted along with a low pulsatility index and calculated flow output on the HeartWare™ monitor. Transesophageal echocardiography showed a hypocontractile and dilated RV with moderate-to-severe tricuspid regurgitation, a dilated inferior vena cava, and no tamponade. Therefore, CPB was reinitiated and a CentriMag® continuous flow right ventricular assist device was implanted. The patient remained intubated and sedated at the completion of the surgery, with his initial postoperative course characterized by significant bleeding requiring aggressive fluid and blood product resuscitation. By postoperative day 5 bleeding had subsided, and he was started on systemic anticoagulation with heparin. On postoperative day 6, as the patient appeared ready to extubate, a large, rapidly expanding hematoma within the abdominal wall adjacent to the HeartWare™ driveline exit site was noted, requiring urgent evacuation.

Key Objectives

- Describe the different types of ventricular assist devices.
- Understand why right heart function is important for proper functioning of a left ventricular assist device.
- Understand why patients with a left ventricular assist device may develop right heart failure.
- List medical interventions that can augment right heart function in patients with a left ventricular assist device.
- Discuss intraoperative strategies that can be used to minimize right ventricular afterload.

Pathophysiology

What types of mechanical circulatory support are available for children?

Mechanical circulatory support (MCS) for children includes extracorporeal membrane oxygenation (ECMO) and ventricular assist devices (VADs). While ECMO provides both cardiac and respiratory support, VADs support only cardiac function. The device chosen for MCS depends on the individual patient's acuity and comorbidities as well as the anticipated length of required support and potential for recovery. Extracorporeal membrane oxygenation can be rapidly instituted in an emergent situation via peripheral vessel cannulation, even during cardiopulmonary resuscitation. This is not true for VAD placement, as it requires a sternotomy and the use of cardiopulmonary bypass (CPB). Furthermore, there is a tremendous amount of experience with ECMO in the pediatric population; it has been used for cardiorespiratory failure in children since the early 1980s. In contrast, the routine use of VADs in adults began in the late 1980s, while in pediatric patients widespread use did not begin until more than a decade later due to the need for technological improvements and device "miniaturization." In pediatric heart failure, implantation of a VAD is most often used as a bridge to transplant or recovery.

Clinical Pearl

Extracorporeal membrane oxygenation provides both cardiac and respiratory support, whereas a VAD only supports cardiac function.

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What types of VADs are commonly used for pediatric heart failure?

There are two broad categories of VADs: those utilized for short-term support (<2 weeks) and those designed for long-term use (>2 weeks).

1. ***Short-term*** devices are ***extracorporeal*** (external to the body) centrifugal pumps. The most commonly utilized devices are RotaFlow® (Maquet, Wayne, NJ); TandemHeart® (CardiacAssist, Pittsburgh, PA); and CentriMag® and PediMag® (Thoratec, Pleasanton, CA).
2. ***Long-term*** devices can be either ***extracorporeal*** or ***intracorporeal*** (within the body), and pumps may provide either pulsatile or continuous flow.
   a. The ***pulsatile flow*** Berlin Heart EXCOR® (BH) device (see Chapter 35) is currently the only US Food and Drug Administration (FDA)-approved pediatric VAD. This pulsatile, extracorporeal VAD has been the most frequently implanted device in pediatric patients and can be used for both LV and biventricular support.
   b. Newer generation ***continuous flow*** pumps have supplanted pulsatile-flow pumps in appropriately-sized patients due to improved safety and the option for hospital discharge. These newer continuous flow devices are intracorporeal and utilize either ***axial or centrifugal*** pumps. Continuous flow devices are almost exclusively used for left heart support in children; however, biventricular support can also be accomplished using two separate pumps. The major drawback with a continuous flow pump is its size, which often precludes use in younger children and instead requires placement of an extracorporeal pulsatile pump. (See Figure 36.1.) The most commonly implanted axial device is the HeartMate II™ (Thoratec), while the most commonly implanted centrifugal pump is the HeartWare™ HVAD™ (HeartWare™ ventricular assist device) (HeartWare, Framingham, MA).

Why is a LV assist device dependent on adequate RV function to work?

Right ventricular output has to increase to match the work of the implanted left ventricular assist device (LVAD). The RV must provide enough flow across the pulmonary vascular bed to provide adequate preload to the LVAD. Therefore, when weaning from CPB after LVAD placement, RV afterload reduction with pulmonary vasodilators such as inhaled nitric oxide (iNO) and milrinone is often utilized and factors that can increase pulmonary vascular resistance (PVR) are avoided. The temporary use of inotropic agents, such as epinephrine, may be required in the immediate postoperative period to improve RV performance and forward blood flow from the right heart to the left. Without adequate filling of the LV, there is collapse of the walls of the LV, restricted inflow into the LVAD, and a reduction in LVAD flow.

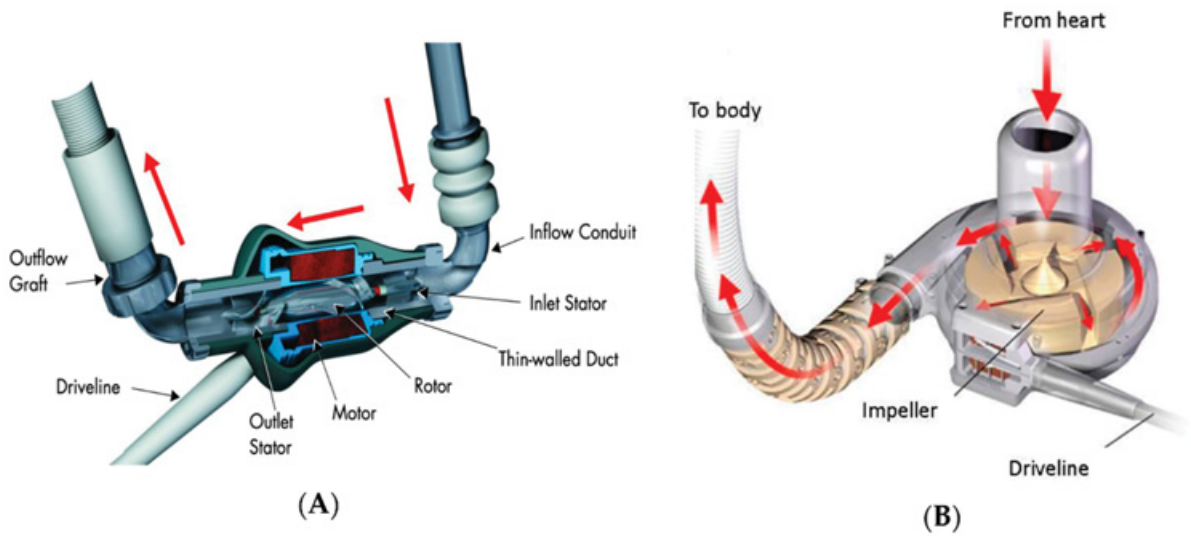

Figure 36.1 Extracorporeal continuous flow left ventricular assist device systems. (A) Axial-flow pump. (B) Centrifugal-flow pump. Figure from Singhvi A. and Trachtenberg B. Left ventricular assist devices 101: Shared care for general cardiologists and primary care. *J Clin Med* 2019; **8**(10): E1720 (PMID 31635239).

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How does RV failure occur in patients supported with an LVAD?

It has been suggested that systolic pressure and stroke volume in the RV are generated by the ability of the RV free wall to contract against the intraventricular septum. Thus, RV failure following LVAD implantation is thought to result from the leftward shift of the intraventricular septum that occurs with excessive unloading of the LV. This shift then causes a decline in RV performance by inhibiting the ability of the RV free wall to effectively contract against the intraventricular septum. Furthermore, with high LVAD flows, the tricuspid annulus may be distorted, which can increase the amount of tricuspid regurgitation. Finally, the augmentation of cardiac output from the LVAD results in increased systemic venous return to the right heart, which can further hinder the performance of an already failing RV, especially if RV afterload is not effectively reduced. Fortunately, this constellation of findings does not happen every time an LVAD is placed. In most cases, the leftward shift of the septum is not excessive and actually improves RV diastolic compliance. In fact, in the absence of pulmonary vascular disease, the off-loading of the LV typically reduces RV afterload and prevents further decline of RV function.

Clinical Pearl

Right ventricular failure following LVAD implantation is thought to result from the leftward shift of the intraventricular septum that occurs with excessive unloading of the LV. This shift then causes a decline in RV performance by inhibiting the ability of the RV free wall to effectively contract against the intraventricular septum.

How is RV failure identified in a patient supported with an LVAD?

Right ventricular failure is defined as the inability of the RV to fill and eject normally, or when the RV cannot provide the pulmonary circulation with adequate blood flow in the presence of a normal preload/central venous pressure (CVP). When present, patients may have symptoms of venous engorgement, hepatomegaly, and fluid retention. The CVP is often elevated and echocardiography may show poor contractility, reduced tricuspid annular plane systolic excursion (TAPSE), and/or right heart dilation. In the presence of an LVAD, RV failure leads to ineffective filling of the LVAD because flow across the pulmonary circulation to the left heart is suboptimal. Inadequate filling of the LVAD is identified by reduced pulsatility and low flow on the HeartWare™ HVAD™ system. This decreased systemic flow reduces end-organ perfusion and can be identified by findings of increased bilirubin, elevated liver function tests, and decreased renal function.

What is a RV assist device?

A right ventricular assist device (RVAD) is a mechanical circulatory device, usually continuous flow, that provides antegrade flow of systemic venous return blood to the pulmonary artery without performing gas exchange. Devices may either be intracorporeal or extracorporeal. Most commonly, MCS for the RV is only required for a short time until RV function can recover. In these situations, an extracorporeal device such as the CentriMag® is commonly inserted. (See Figure 36.2.) The CentriMag® (see Figure 36.3) is a continuous flow device with two cannulas, one draining the right heart and a second returning blood to the pulmonary artery. Similarly to a continuous flow LVAD, the speed of the RVAD is programmed to achieve the desired amount of flow. Adequate decompression of the right heart is best evaluated with echocardiographic imaging and assessment of LVAD performance.

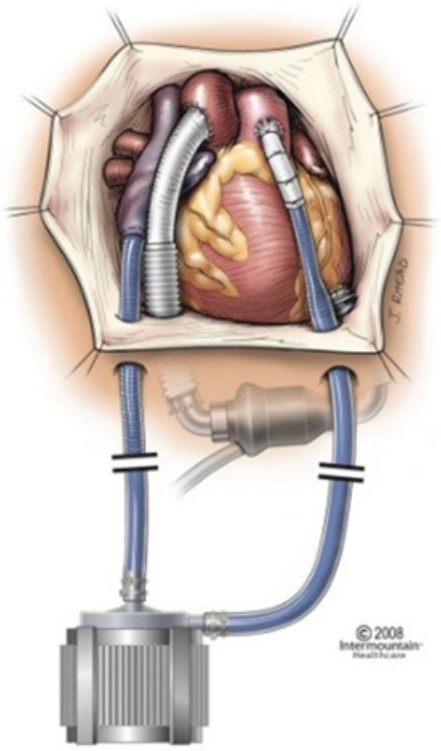

Figure 36.2 Extracorporeal CentriMag® RVAD is shown connected to cannulas that enter the body and are connected to the heart and great vessels. A continuous flow HeartMate II™ LVAD is also depicted. Figure used with permission from Intermountain® Healthcare.

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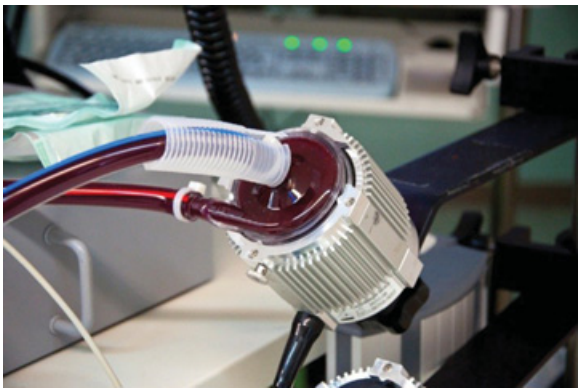

Figure 36.3 CentriMag® extracorporeal continuous flow pump used to support the RV. Image from www.flickr.com/photos/ec-jpr/9243359624

Why is an RVAD not always placed at the same time as an LVAD in children with heart failure requiring MCS?

Patients with heart failure who are candidates for an LVAD can have a broad range of RV dysfunction. Right ventricular function typically improves in many patients after placement of an LVAD. However, in some patients RV failure may persist. Many of these patients improve with medical management alone, but those who do not can be mechanically supported with an RVAD. An RVAD can be placed either at the time of LVAD placement or soon thereafter. Patients requiring biventricular mechanical support (BiVAD) have higher mortality, irrespective of the timing of RVAD placement. It remains unclear how much of the reduced survival associated with BiVAD support is due to the morbidity of having a second device, or if it is secondary to the severity of the underlying heart failure necessitating BiVAD support. Because there are no established criteria for RVAD implementation in children, centers often prefer aggressive medical therapy for RV dysfunction as first-line management. However, if mechanical support seems unavoidable, early RVAD implantation is recommended.

Anesthetic Implications

The patient is receiving systemic anticoagulation with a heparin infusion to prevent device-associated thrombus formation. How should anticoagulation be managed for the upcoming procedure?

Anticoagulation management for patients on MCS is complex. The risk for thrombus formation due to foreign material is not trivial and must be balanced against the risk of hemorrhage. Initiation of systemic anticoagulation does not generally occur until postoperative bleeding has subsided, typically on postoperative day 2 or 3. This patient has a hematoma that likely formed following surgery and then acutely worsened with the initiation of anticoagulation. Monitoring of anticoagulation parameters (activated partial thromboplastin time [aPTT], prothrombin time/international normalized ratio [PT/INR], antifactor Xa, and thromboelastogram) helps guide therapies. While minor surgeries may not require anticoagulation to be discontinued, major surgeries or surgeries with a high risk of bleeding (i.e., neurosurgical) may require adjustments. Therefore, a consensus among providers (intensivist, cardiologist, surgeon, anesthesiologist) or the team managing anticoagulation must be reached regarding the risk/benefit ratio of continuing, discontinuing, or modifying management of anticoagulation in the perioperative period prior to every surgical intervention. The surgical evacuation of a hematoma is a relatively minor surgery and anticoagulation could most likely be discontinued for a brief period. However, if there is concern for thrombus formation in either device (which would be unusual at this early stage in the postimplantation period), the risk of even briefly discontinuing anticoagulation may outweigh the risk of continuing it through the perioperative period.

Clinical Pearl

A consensus among providers (intensivist, cardiologist, surgeon, and anesthesiologist) must be reached regarding the risk-benefit ratio of continuing, discontinuing, or modifying anticoagulation in the perioperative period prior to every surgical intervention.

The surgeon requests that the procedure be performed in the operating room. Is this reasonable and if so, which additional staff can provide valuable assistance with this procedure?

Transporting any patient on life-sustaining technology presents unique challenges and risks. This patient has two mechanical devices supporting his heart. The CentriMag® RVAD system is an extracorporeal device residing outside of the body and connected to a control unit. (See Figure 36.4.) The implanted HVAD™ also has a dedicated control console. Both of these devices require trained personnel (either VAD specialist and/or perfusionist) to be immediately present. Any movement of the patient

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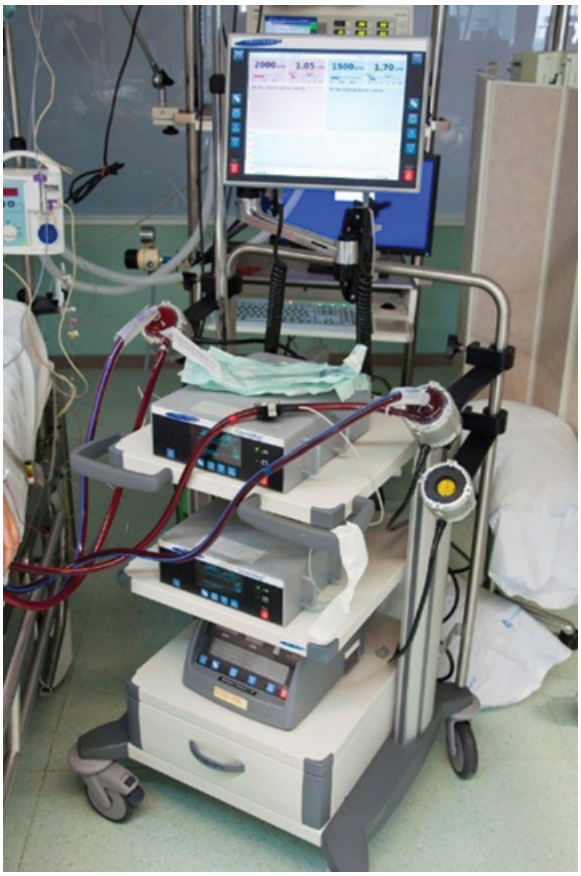

Figure 36.4 Example of a control unit for an extracorporeal, continuous-flow mechanical circulatory system. Image from www.flickr.com/photos/ec-jpr/9243362372/in/photostream/

requires meticulous attention to cannula position and integrity to maintain optimal pump flow and prevent catastrophic disconnections. If transportation of the patient is absolutely required, then all appropriate personnel must accompany the patient.

Given the risks associated with transport and the scope of the proposed surgery, it is reasonable to discuss with the surgeon whether the hematoma evacuation can be safely performed in the intensive care unit (ICU) at the bedside.

Clinical Pearl

Transporting a patient on extracorporeal mechanical support requires thoughtful planning, and every effort to perform tests and procedures at the patient's bedside should be made when appropriate. Any movement of the patient requires meticulous attention to cannula position and integrity to maintain optimal pump flow and prevent catastrophic disconnections.

The surgeon is amenable to performing the procedure in the ICU, but requests that the patient receive a general anesthetic provided by an anesthesiologist. Currently the patient is receiving morphine and dexmedetomidine infusions for sedation while mechanically ventilated. How should an anesthetic be planned?

Since the procedure is being performed in the ICU, there is no anesthesia machine to administer inhalational volatile agents. Therefore, a total intravenous anesthetic is the best choice. Because chronically ill patients who are mechanically ventilated in the ICU often require high doses of sedative infusions over prolonged periods, they often develop significant tolerance. Therefore, simply increasing the background sedative infusions may not be adequate to provide a surgical depth of anesthesia. Additional amnestic and analgesic drugs (i.e., propofol, ketamine, midazolam, or a combination) are necessary. It can be helpful to use bispectral index monitoring in this situation to assess the depth of anesthesia.

What important preparation is necessary for this patient when performing a general anesthetic in the ICU?

The presence of a VAD with the subsequent administration of anticoagulant and antiplatelet agents places patients at increased risk for bleeding during surgical procedures. Therefore, it is prudent to have appropriate cross-matched blood products immediately available along with all proper equipment (i.e., blood warmer with filter and tubing) required to rapidly administer blood products. In addition, all medications (emergency and anesthetic) and airway equipment normally available in the OR should be brought to the patient's bedside in the ICU. The anesthesia team should also familiarize themselves with the ICU ventilator, and a respiratory therapist should be available for ventilator adjustments or troubleshooting if required. Finally, bedside monitors should be positioned so that both the anesthesia team and surgeons can easily observe intraoperative hemodynamics.

Clinical Pearl

The presence of a VAD and the ongoing administration of anticoagulant and antiplatelet agents places patients at increased risk for bleeding during surgical procedures. Therefore, it is prudent to have appropriate cross-matched blood products immediately available.

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How should the intraoperative plan be designed to maintain low PVR and ensure adequate HVAD™ filling and flow?

As an LVAD is preload dependent, LV filling must be maintained to ensure adequate systemic flow. Systemic venous return to the right heart must be pumped across the pulmonary vascular bed before it reaches the left heart. Any pathology that inhibits this forward flow of blood can lead to inadequate HVAD™ filling, therefore limiting the systemic flow that can be generated. Right heart pathology (i.e., tricuspid regurgitation, ventricular dysfunction, pulmonary valve insufficiency) disrupts flow of blood into the pulmonary vasculature. Downstream from the RV, pulmonary vascular pathology (i.e., pulmonary hypertension, pulmonary artery stenosis, pulmonary vein stenosis) and mitral valve disease (i.e., mitral stenosis and mitral regurgitation) can also contribute to poor LV filling. While some of these factors may not be amenable to manipulation, those that can be optimized are important in the intraoperative management of these patients. The primary goal is to avoid elevations in RV afterload by maintaining low PVR. Avoiding triggers that elevate PVR, such as hypercarbia, acidosis, hypoxemia, hypothermia, and sympathetic stimulation, is of the utmost importance. Pulmonary vasodilators such as iNO or prostacyclin analogues may be considered to reduce PVR.

Reviewing the most recent chest radiograph and blood gas prior to the start of surgery is important to gain a qualitative estimation of current pulmonary pathology. Periodic monitoring of blood gases and continuous end-tidal CO_2 monitoring throughout the case aids in guiding ventilator manipulations. Care must be taken to avoid extremes of mean airway pressure, as both overdistention and underinflation of the lungs can lead to elevations in PVR. Ensuring an adequate depth of anesthesia/analgesia can prevent increases in PVR that can occur with sympathetic stimulation from painful procedures. Should a sudden increase in RV afterload occur, a chest radiograph or point-of-care ultrasound of the lungs should be performed to rule out intrathoracic pathology (i.e., pneumothorax or hemothorax).

Clinical Pearl

The primary goal is to avoid elevations in RV afterload by maintaining low PVR. Avoiding triggers that elevate PVR, such as hypercarbia, acidosis, hypoxemia, hypothermia, and sympathetic stimulation, is of the utmost importance.

In patients with an RVAD, what considerations are important to ensure adequate blood flow into the pulmonary circulation?

In patients with an RVAD, the forward flow of blood from the right heart to the pulmonary circulation is largely dependent on RVAD flow, and to a lesser degree, RV function. If a decrease in RVAD flow occurs, the etiology should be determined, and appropriate measures undertaken.

A decrease in RVAD flow can occur from any of the following:

- Decreased inflow (i.e., hypovolemia, inflow cannula obstruction)
- Pump failure (i.e., thrombosis)
- Increase in afterload (i.e., outflow cannula obstruction, increased PVR)

Information obtained from the perfusionist's assessment of the pump and circuit can often help narrow the possible etiologies. Echocardiographic images can also be extremely useful; therefore, placement of a transesophageal probe should strongly be considered during surgical procedures, especially if large fluid shifts are expected. Transesophageal echocardiography can evaluate device cannula position, ventricular filling, and ventricular function, all of which can help guide intraoperative therapy. With satisfactory echocardiographic imaging, if the patient is not hypovolemic and there is no concern for pump thrombosis or elevated PVR, increasing the RVAD speed to increase flow should be considered. However, the ability to increase RVAD speed may be limited by cannula size. If increasing RVAD speed cannot safely be performed, use of an inotropic agent to promote RV contractility while under anesthesia should be considered.

Clinical Pearl

It is important to consider the RVAD and RV as two separate components contributing to right ventricular stroke work. In the majority of patients with an RVAD, the RV function is usually limited; however, as the RV recovers, the overall amount of work the RVAD contributes to RV stroke work decreases. This then allows the RVAD speed to be incrementally decreased until it is low enough that it can be eventually explanted/removed. In situations in which right heart stroke work needs to increase, either the RVAD speed or RV contractility can be augmented.

Does an RVAD provide respiratory support?

An RVAD does not provide respiratory support. An RVAD system is slightly different from a veno-venous (VV) ECMO circuit. In VV-ECMO, systemic venous

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blood is removed and returned to the right heart after traveling through an oxygenator. The purpose of VV-ECMO is to support patients with lung injury by providing gas exchange (adding oxygen and removing carbon dioxide). It requires adequate RV function to operate properly. In contrast, an RVAD system is intended to only support depressed RV function. It is possible to place an oxygenator in the extracorporeal RVAD circuit to support gas exchange, but this is not common. Of note, an RVAD can indirectly improve oxygenation and ventilation by improving pulmonary blood flow, thereby reducing dead space.

Clinical Pearl

Veno-venous ECMO can support patients with lung injury by providing gas exchange (adding oxygen and removing carbon dioxide). It requires adequate RV function to operate properly. In contrast, an RVAD system is intended to only support depressed RV function.

Suggested Reading

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