Chapter

70

Ventricular Assist Devices

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A three-month-old previously healthy infant presents to the emergency room with increased work of breathing and a two-week history of rhinorrhea and cough. Chest X-ray demonstrates severe cardiomegaly prompting an echocardiogram which reveals severe left ventricular dilation compressing the right ventricle (RV) severe mitral regurgitation, and severely depressed biventricular function. The differential includes viral myocarditis versus dilated cardiomyopathy.

Over the next week, the patient is intubated for respiratory distress and started on inotropic support to optimize cardiac output. In the past 12 hours, the infant has become increasingly tachycardic to the 180s–190s and hypotensive with blood pressures between 45–55/30–40 in spite of escalating inotropy. Labs are significant for increasing creatinine and elevations in liver enzymes. Oxygenation, ventilation, and lung compliance are stable. Due to concerns regarding impending circulatory collapse, the patient is taken to the OR for initiation of mechanical circulatory support via the Berlin Heart EXCOR ventricular assist device (VAD, Berlin Heart GmbH, Berlin, Germany).

Following device placement and stabilization of hemodynamics and bleeding, the patient is extubated, and anticoagulation is started. Two weeks thereafter, the patient becomes acutely hypotensive with decreased device filling. A large black stool is concerning for a gastrointestinal bleed. With continued instability in spite of transfusion, the patient is taken the operating room for exploratory laparotomy.

What Are the Indications for Ventricular Support in Children?

Heart failure in children can be the end result of multiple causes, with common culprits being congenital heart disease, cardiomyopathies, and myocarditis. While many of these patients can be medically or surgically managed, a minority will require mechanical circulatory support in order to maintain end-organ perfusion, either in the form of a VAD or extracorporeal membrane oxygenation (ECMO). Such support can be used as a bridge-to-recovery, bridge-to-transplantation, or bridge-to-decision.

How Is a VAD Different than ECMO?

While both a VAD and ECMO can provide short-term circulatory support, ECMO offers the additional ability to oxygenate and ventilate using the membrane oxygenator. The oxygenator, although beneficial to those in respiratory failure, also promotes an inflammatory response that can adversely affect hemodynamics as well as coagulation. A VAD functions only as ventricular support, does not use an oxygenator, and thus avoids this inflammatory insult.

VADs are better able to decompress the left ventricle (LV) in comparison to ECMO due to their placement in either the left atrium or left ventricle. A secondary goal of mechanical circulatory support is to rest the left heart by minimizing its preload. On ECMO, blood may return to the left ventricle either by inadequate venous drainage or by the presence of aortopulmonary collaterals. This leads to stretching of the left ventricular myocardium with a subsequent increase in oxygen consumption. The increase in left-sided filling may result in left atrial hypertension and worsened pulmonary dysfunction through increased pulmonary venous pressures. To manage the increase in LV pressure, some patients on ECMO require balloon atrial septostomy.

Moreover, while ECMO runs are generally limited (weeks to months) due to its associated complications, short-term VADs achieved through central cannulation can be transitioned more easily to durable VADs to allow for much longer periods of support (months to years).

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In Which Situations Would ECMO Be a Better Choice than a VAD?

ECMO is most commonly deployed in the setting of cardiac arrest (extracorporeal cardiopulmonary resuscitation or ECPR) or acute postcardiotomy dysfunction. ECMO would be the preferred choice in patients with pulmonary as well as circulatory failure, or in patients with acute biventricular failure. Clinical scenarios like severe pulmonary edema in the setting of ventricular dysfunction, right ventricular failure due to pulmonary hypertension, or hemodynamic instability due to sepsis would qualify.

What Determines the Timing of Device Placement?

The ideal time to move forward with device placement remains a challenge in pediatrics. Influencing this decision are the patient's clinical course, body size, and relatedly, the device options available. The goal is to initiate support prior to the development of irreversible end-organ injury, or when medical therapy has failed. Such endpoints are difficult to define as patients can have variable clinical courses with intermittent periods of decline and improvement. Moreover, the devices available to children are not without risk. The Berlin EXCOR is the only VAD currently approved for use in neonates and infants but has a markedly higher rate of pump thrombosis compared to continuous flow VADs. And while larger children and adolescents can accommodate continuous flow VADs like the Heartmate II (Thoratec Corp., Pleasanton, CA) or HeartWare HVAD (HeartWare, Framingham, MA), the experience with these devices in children remains limited. In this setting, the medical team must weigh the risk of device placement versus the risk of worsening end-organ injury with continued medical management alone. A temporary support device or ECMO may be an option in such cases to allow for recovery of end-organ function before placement of a long-term device.

How Do We Select the Type of VAD to Place?

Different algorithms have been generated to assist with device selection. Relevant factors considered include (1) the type of support needed: cardiac-only, cardiopulmonary, left versus right ventricular support, or biventricular support; (2) the anticipated duration of support; and (3) the size of the patient. There are now many devices suitable for use in children (Figure 70.1).

What Are the Options for Temporary and Long-Term Support Devices?

Temporary VADs are deployed for settings in which myocardial function may recover within one to two weeks or if end-organ stabilization is desired prior to placement of a long-term VAD or heart transplant. Options for temporary VADs include the PediMag (Thoratec Corporation), RotaFlow (Maquet), TandemHeart (Cardiac Assist, Inc), and Impella (Abiomed), all continuous-flow devices. The PediMag and RotaFlow are extracorporeal centrifugal pumps that can support the range of pediatric sizes, assist both the right and left ventricle, and connect to centrally placed cannulas. The TandemHeart and Impella, in contrast, are percutaneously placed. Due to the size of the sheaths necessary to deploy these devices, their use is limited to large children and adolescents.

Durable or long-term VADs include both pulsatile and continuous-flow devices. They serve as bridges to transplantation, or rarely, as destination therapy. For infants and small-children, the sole device available is the Berlin Heart EXCOR, a pneumatically driven paracorporeal pulsatile pump. In adolescents and larger children, the size mismatch between "adult" devices and the patient is of lesser concern, and so continuous-flow devices such as the Heartmate II and HeartWare are chosen due to their lower risk profile. An alternative option to continuous-flow devices in larger patients is the SynCardia Total Artificial Heart (SynCardia Systems, Inc., Tucson, AZ), a pneumatically-driven device that entirely replaces the valves and ventricles of the native heart.

Which Noncardiac Procedures Are Most Commonly Performed on Patients with VADs?

The range of diagnostic and therapeutic procedures for which these patients can present is broad and include both those related to device complications and the routine management of the critically ill child. Noninvasive procedures most commonly entail

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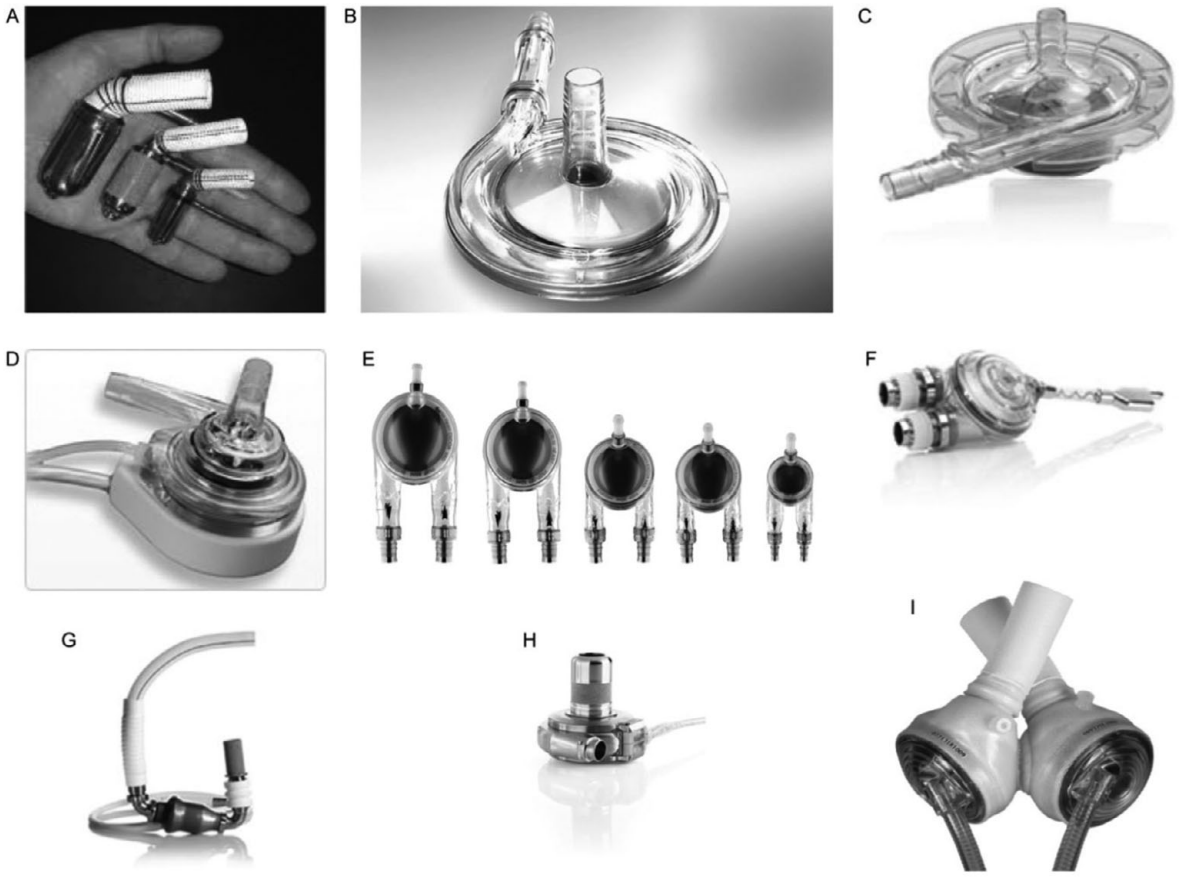

Figure 70.1 Ventricular assist devices. (A) The Jarvik 2000 devices, left to right adult, child and infant Jarvik. (B) The RotaFlow assist device. (C) The PediMag assist device. (D) The TandemHeart assist device. (E) Variety of Berlin Heart EXCOR devices from left to right 60, 50, 30, 25, 10 mL. (F) Thoratec assist device. (G) Heartmate II assist device. (H) Heartware assist device. (I) SynCardia total artificial heart. Reproduced with permission of John Wiley and Sons, from Mascio CE. *Artif Organs* 2015 Jan;39(1):14-20

imaging studies like CT (MRI is contraindicated due to the device). Invasive procedures include those needed for venous access, imaging of the heart and device via transesophageal echocardiography, or to address otolaryngologic, general surgical, or neurosurgical issues. For those patients with the Berlin Heart EXCOR, device exchange is commonly performed due to the presence of fibrin strands or clot in the pump.

What Preoperative Information Should One Collect Prior to Planning an Anesthetic?

An evaluation of the patient's underlying cardiac history, native ventricular function, end-organ dysfunction, and device type are essential. To help in this process, the input of the patient's cardiologist, cardiac surgeon, or VAD coordinator can be elicited. Complications incurred following device placement should also be sought. These can entail bleeding or thromboembolic events that can manifest as neurologic sequelae like strokes or seizures, gastrointestinal bleeds, or pump thrombosis. The balance between clotting and bleeding is tenuous in VAD patients, and a review of the patient's anticoagulation strategy and current level of anticoagulation may assist in assessing bleeding risk and in deciding which blood products to order.

Other device risks to assess include infection, which may influence the choice of perioperative antibiotics, and the presence of persistent renal or hepatic

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dysfunction. Even following VAD placement, patients can be anuric and require continuous renal replacement therapy or intermittent dialysis due to the extent of end-organ injury experienced in the pre-device period. Such knowledge may impact anesthetic drug choice or the type and amount of volume to be administered intraoperatively.

What Device Parameters Should One Assess in the Berlin Heart EXCOR, Heartmate II, and Heartware?

Berlin Heart EXCOR

- Pump rate
  - Operates at a predetermined rate but is adjustable
  - Pump rate × device volume = cardiac output delivered by the device
- Per cent time in systole
  - Set to mimic native physiology in which diastole is longer than systole
- Systolic pressure
  - Set higher than the native systolic blood pressure
- Diastolic pressure
  - Set higher than the native diastolic pressure
- Adequacy of pump filling and ejection
  - Assessed by direct inspection of the pump
    - Wrinkling of the chamber in diastole indicates inadequate fill
    - Wrinkling of the chamber in systole indicates impaired ejection
- Battery life prior to transport

Heartmate II

- Pump speed (RPM)
  - Optimized using echocardiography to achieve the desired physiologic response
  - Operates at the predetermined rate with the ability to decrease speed during suction events (i.e., when the LV sucks down or collapses due to hypovolemia, RV failure, or tamponade)
- Power (watts)
  - A direct measure of motor voltage and current
  - ↑ pump speed > ↑ power
- Pulsatility index (PI): 110 scale
  - Corresponds to the magnitude of pulsatility seen by the pump
    - A function of how well the native heart is contracting and pump speed
  - As the native ventricle contributes more to ejection, more pulsatility is seen by the pump
  - As the pump speed increases, the ventricle is more unloaded and pulsatility decreases
  - A higher PI thus indicates less support by the pump, whereas a lower PI indicates more support
  - Fluctuates with volume status, SVR, and biventricular function
- Flow (L/min)
  - An estimated value based on power, pump speed, and viscosity (hematocrit)
    - ↑ power > ↑ flow
    - ↑ pump speed > ↑ flow
  - Used as a trend monitor rather than an actual reflection of cardiac output
  - Low flow may be secondary to any process that impairs device filling and ejection
    - Inflow or outflow graft occlusion
    - Hypovolemia
    - Right ventricular dysfunction
    - Elevated PVR
    - Increased SVR
  - High flows in the setting of gradual increases in power should raise suspicion for pump thrombosis
    - High flows in this setting are artifactual as they are based on power
- Battery life prior to transport

Heartware

- Pump speed (RPM)
  - Operates at the predetermined rate, but speed does not decrease during suction events

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Table 70.1 Examples of commonly used parameters in selected support devices

Heartmate II			
RPM	**Power (watts)**	**Pulsatility Index**	**Flow (L/min)**
9600 (6000 – 15000)	7	3.6 (1–10)	4.5
Berlin Heart EXCOR			
Rate	**% Time in systole**	**Systolic Pressure**	**Diastolic Pressure**
80	40%	220 mm Hg	-40 mm Hg
Heartware			
RPM	**Power (watts)**	**Flow (L/min)**	
2400–3200	2.5–8.5	3–8	

- Power (watts)
- Flow (L/min)
- Flow pulsatility (amplitude)
  - Similar to the pulsatility index in the Heartmate II
    - Difference between the peak and trough flows
    - Recommended >2 L/min in order to avoid retrograde flow or suction events
    - Reflects pump speed as well as LV preload, afterload, and native contractility
- Battery life prior to transport

Examples of device-specific parameters are identified in Table 70.1.

What Are the Physiologic Principles to Consider When Anesthetizing a Patient with a VAD?

Device filling is dependent on adequate preload and sufficient right ventricular function. As such, efforts should be made to attain euvolemia and minimize pulmonary vascular resistance (PVR) via adequate oxygenation, ventilation, and analgesia while avoiding acidosis. For those patients who have pre-existing depressed right ventricular function or elevations in PVR, inotropic support can be used to bolster the ventricle in the perioperative period while inhaled nitric oxide can be used to further decrease PVR. Spontaneous ventilation can also be considered if the procedure allows for its beneficial effects on PVR, venous return, and hemodynamic stability compared to positive pressure ventilation, especially for the RV.

Maintenance of systemic vascular resistance (SVR) is also necessary to minimize periods of hypotension. Anesthesia-induced vasodilation leads to a decrease in SVR and increased venous capacitance that can produce hypotension out of proportion to that expected with standard anesthetic dosing. This hypotension further reduces preload to the right heart, thereby diminishing both left ventricular and device filling. Vasopressors such as phenylephrine, norepinephrine, or vasopressin are often required to counteract these effects.

What Monitors, Special Equipment, and Personnel Should One Plan For?

Standard monitors are often sufficient for noninvasive procedures or for those in which significant fluid or hemodynamic shifts are not anticipated. Of note, the ECG in patients with the Berlin Heart reflects native contractions and not the device rate selected on the console. The native rhythm merits monitoring, nonetheless, as arrhythmias may influence right ventricular function, and thus device filling.

In patients with continuous-flow devices, a noninvasive blood pressure cuff can provide an accurate measurement due to the native contractility of the left ventricle. Exceptions include those patients with severely depressed left ventricular function and minimal pulsatility. Arterial line placement using ultrasound or Doppler guidance is then indicated. Consideration should also be given to the accessibility of the patient's arms should arterial access be needed during the case. Given these patients' propensity to develop hypotension with anesthesia, the threshold to place an arterial line should be low if the arms are to be tucked or draped.

For more involved procedures, central venous catheters and transesophageal echocardiography can

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be used to guide fluid management and inotropy, particularly when response to traditional measures to improve hemodynamics has failed. Cerebral perfusion can also be trended using near-infrared spectroscopy probes.

Critically, a perfusionist or member of the institution's VAD team should be available to help with device management and transport whenever a patient is in need of an anesthetic.

What Blood Pressures Should Be Targeted with These Devices?

A reasonable target may be the patient's baseline pressures following stabilization on the device and recovery of end-organ function. For continuous-flow devices, target mean arterial pressure should be comparable to age-appropriate goals and can be adjusted to the perfusion needs of the individual. Pulsatile devices, similarly, should aim to generate an age-appropriate systolic and diastolic pressure. Factors that may skew the patient's pressures include patient-pump size mismatch or persistently elevated SVR following implantation.

Which Induction and Maintenance Regimens Result in the Least Hypotension?

Clinical experience and study suggest that ketamine may offer the most hemodynamically stable anesthetic induction in patients with VADs. This is likely secondary to its ability to maintain SVR through increasing circulating levels of catecholamines. For maintenance, age-appropriate levels of anesthetics often lead to hypotension, suggesting a minimal therapeutic window. Specifically, significant hypotension has been observed with sevoflurane >1%, desflurane >2%, propofol >50 mcg/kg/min, and remifentanil >0.01 mcg/kg/min. Compared to remifentanil, fentanyl, or sufentanil may better preserve SVR. Such data underscores the frequent need for volume resuscitation and pressor support simply to provide a minimal anesthetic in this patient population.

Can a Patient with a VAD Be Externally Cardioverted or Defibrillated in the Event of a Malignant Arrhythmia?

Yes. While an left ventricular assist device (LVAD) will continue to function during an arrhythmia, the filling of the left heart may be impaired by the decreased right ventricular output. During attempts at external cardioversion or defibrillation, the patient can remain connected to the device and the pads should be placed such that they do not directly overlie the implanted pump. In patients who have been fibrillating for an unknown or long period of time, the risk of thromboembolism due to the development of thrombus must be considered.

Can Chest Compressions Be Performed on Those with VADs?

Yes. Though there is a risk of device and cannula dislodgement or malposition, chest compression should be performed if indicated by pediatric advanced life support. Supporting this practice is one retrospective review which found no dislodgement and 50% return of neurologic function in eight LVAD patients who received chest compressions while in cardiac arrest. Additional therapy in the setting is aimed at supporting the right ventricle by providing oxygenation, ventilation, and pharmacologic assistance.

Algorithm for Managing Perioperative Hemodynamic Changes

The perioperative management algorithms for patients with VAD support are summarized in Tables 70.2 and 70.3.

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Berlin Heart EXCOR

Table 70.2 Perioperative management algorithms for patients supported by the Berlin Heart

	Potential etiologies	HR (native)	CVP	Device inspection	Treatment
Hypotension	Hypovolemia	↑	↓	Wrinkling/ poor fill in diastole	Give volume; increasing device rate not recommended (will decrease fill time)
	Vasodilation	↑	↔	Chamber may fill completely	Alpha-agonists, vasopressin
	RV failure	↑↑	↑↑	Wrinkling/ poor fill in diastole	Inotropy, iNO, maneuvers to decrease PVR
	Tamponade	↑↑	↑↑	Wrinkling/ poor fill in diastole	Surgical exploration
Hypertension	Pain	↑↑	↑, ↔	Wrinkling/ poor emptying in systole	Analgesia; avoid increasing systolic driving pressure > 195 mm Hg
	Awareness	↑↑	↑, ↔	Wrinkling/ poor emptying in systole	Sedation, analgesia
	Hypervolemia	↔	↑↑	Full fill in diastole, poor emptying in systole	Increase device rate, diuresis
Thrombus	Inadequate anticoagulation	↔, ↑↑ if large/occlusive, cardiac output would be determined by native cardiac function	↔, ↑↑ depending on severity of occlusion	Fibrin strands on valves or larger clot	Pump change

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Continuous-Flow Devices

Table 70.3 Perioperative management algorithms for patients supported by the continuous flow devices (e.g., Heartware)

	Potential etiologies	HR (native)	CVP	Heartmate II	HVAD	Treatment
Hypotension	Hypovolemia	↑	↓	↓ Pulsatility Index (PI); ↓ in RPMs (lowest 6000) beyond which the device will stop until volume is replete	↓ amplitude RPMs do not decrease as in the Heartmate II unless changed manually	Give volume, ↓ RPMs in the HVAD to prevent a suction event
	Vasodilation	↑	↔	↑ flow with ↔ in RPM	↑ flow with ↔ in RPM	Alpha-agonists, vasopressin
	RV failure	↑↑	↑↑	↓ PI and watts	↓ amplitude and watts	Inotropic support, iNO, maneuvers to decrease PVR
	Tamponade	↑↑	↑↑	↓ PI and flow	↓ amplitude and flow	Surgical exploration
Hypertension	Pain	↑↑	↑, ↔	↓ flow with ↔ in RPM	↓ flow with ↔ in RPM	Analgesia
	Awareness	↑↑	↑, ↔	↓ flow with ↔ in RPM	↓ flow with ↔ in RPM	Sedation and analgesia
	Hypervolemia	↔	↑↑	↓ flow	↓ flow	Increase RPMs and diuresis
Thrombus	Inadequate anticoagulation	↔, ↑↑ depending on severity of occlusion	↔, ↑↑ depending on severity of occlusion	↑ watts and flow (artifact of increased watts)	↑ watts and flow (artifact of increased watts)	Heparin or pump exchange

Suggested Reading

Cooper DS, Pretre R. Clinical management of pediatric ventricular assist devices. *Pediatr Crit Care Med*. 2013;14:S27–36. PMID: 23735982.

Jaquiss RDB, Bronicki RA. An overview of mechanical circulatory support in children. *Pediatr Crit Care Med*. 2013;14(5 Suppl 1):S3–6. PMID: 23735983.

Mascio CE. The use of ventricular assist device support in children: the state of the art. *Artif Organs*. 2015;39(1):14–20. PMID: 25626575.

Mossad EB, Motta P, Rossano J, et al. Perioperative management of pediatric patients on mechanical cardiac support. *Paediatr Anaesth*. 2011;21(5):585–93. PMID: 21332879.

Pratap JN, Wilmshurst S. Anesthetic management of children with in situ Berlin Heart EXCOR. *Paediatr Anaesth*. 2010;20(12):1137–8. PMID: 21199125.

Stein ML, et al. Ventricular assist devices in a contemporary pediatric cohort: Morbidity, functional recovery, and survival. *J Heart Lung Transplant*. 2016; 35:92–98. PMID: 26210751.

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