Chapter 35

Left Heart Ventricular Assist Device

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Case Scenario

A 5-year-old male weighing 17 kg presents from the cardiac step-down floor with melena and a drop in hematocrit from 33% to 26% over 72 hours. The patient is to undergo an upper endoscopy in the operating room.

He has a history of dilated cardiomyopathy and underwent placement of a Berlin Heart left ventricular assist device 2 months earlier. His current vital signs are pulse rate 98 beats/minute, respiratory rate 20 breaths/minute, blood pressure 124/94, temperature 36.6°C, and SpO_2 100% on room air.

Current Berlin Heart settings are left systole 205 mm Hg; left diastole 25 mm Hg; left rate 98 beats/minute; 40% left systole. Monitoring parameters: fill: partial to full; emptying: 100%.

Key Objectives

- Understand the mechanics of the Berlin Heart.
- Describe indications for placement of a Berlin Heart.
- Discuss comorbidities experienced by Berlin Heart patients.
- Describe specific considerations in providing anesthesia for a patient with a Berlin Heart.

Pathophysiology

What is a ventricular assist device?

A ventricular assist device (VAD) is a mechanical pump used to support failing heart function when medical therapies have been exhausted.

Ventricular assist devices are most often classified according to the mode of blood flow generated by the pump:

- ***Pulsatile pumps*** mimic the natural pumping action of the heart. The Berlin Heart EXCOR (which this patient has implanted) is a paracorporeal pulsatile system. The 50cc Total Artificial Heart (SynCardia Systems, Inc.) is another pulsatile system, albeit a biventricular system, that is currently in clinical trial. It may be suitable for pediatric patients aged 10–18 years with a body surface area (BSA) down to 1.2 m^2, and possibly even smaller patients with virtual implantation.
- ***Continuous flow pumps*** are further characterized by the type of mechanical pump utilized. An ***axial pump*** generates flow by rotating an impeller and causing blood to be accelerated in the direction of the rotor's axis. The HeartMate II (Thoratec Corporation) device is an example of an axial continuous flow pump.
  A ***centrifugal pump*** draws blood in along a central axis and expels it tangentially by the impeller blades of the rotor. Centrimag (Thoratec Corporation), HeartMate 3 (Thoratec Corporation), and HeartWare (HeartWare Systems) devices utilize centrifugal pumps.

  All VADs share the following components:
  - Inflow and outflow cannulas
  - Pump
  - Power source with driveline
  - System controller
  - Clinical monitor console that can be attached to the controller to interrogate the device

How is the type of VAD selected for a child?

Device selection factors include the following:

- Underlying disease and cause of heart failure
- Duration of need for circulatory support
- Type of ventricular support needed (left, right, or biventricular)
- Patient's weight and body surface area
- Discharge potential

What is unique about the Berlin Heart EXCOR VAD?

The Berlin Heart EXCOR (Berlin Heart GmbH) is the only Food and Drug Administration (FDA)-approved VAD for long-term support of younger children with low cardiac output syndrome. It is a paracorporeal system that consists

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of a pulsatile blood pump with an electropneumatic drive system. It can be used for right (RVAD), left (LVAD), or biventricular (BiVAD) support. (See Figure 35.1.) The pump is available in a range of sizes with different stroke volumes suitable for neonates through adolescence. (See Figure 35.2.) Inlet and outlet connectors with tri-leaflet, one-way valves (Sorin-type tilting metal disks in larger devices) ensure unidirectional blood flow into and out of the heparin-coated blood chamber that is separated from an air chamber by a flexible, triple-layered membrane diaphragm. This curved diaphragm is driven by alternating pressures generated via the single driveline to the driving system unit: positive pressure applied essentially ejects blood out of the blood chamber into the patient's circulation, while negative pull entrains blood into the chamber during a fill cycle. The pump rate setting determines how often the membrane moves in 1 minute. The rate should be chosen such that the resulting blood flow meets the patient's requirements.

Cannulas are an important part of the Berlin Heart (BH) system and are constructed of noncoated reinforced silicone with a suture ring to facilitate anastomosis. The Dacron-velour mid-portion that exits the skin supports tissue ingrowth and thus protects against tracking infection. The availability of varied types and sizes of BH cannulas with differing lengths, angles, and tip styles has enabled a broader application for these cannulas compared with other devices. (See Figure 35.3.) Berlin Heart cannulas have been used for transthoracic extracorporeal life support with a temporary device when the outlook for native cardiac recovery is poor, thus allowing conversion to a BH pump without reopening the chest.

Figure 35.1 Biventricular support with two Berlin Heart devices. LVAD configuration has inflow cannula in the LV apex, with outflow to the aorta. RVAD configuration has inflow from the right atrium, with outflow to the pulmonary artery. Reproduced with permission of Berlin Heart Inc.

Clinical Pearl

The Berlin Heart EXCOR is the only FDA-approved VAD for long-term support of younger children with low cardiac output syndrome. It can be used for right, left, or biventricular support.

Figure 35.2 The wide range of pump sizes broadens the applicability of the Berlin Heart EXCOR to all pediatric ages from neonates to adolescence. Reproduced with permission of Berlin Heart Inc.

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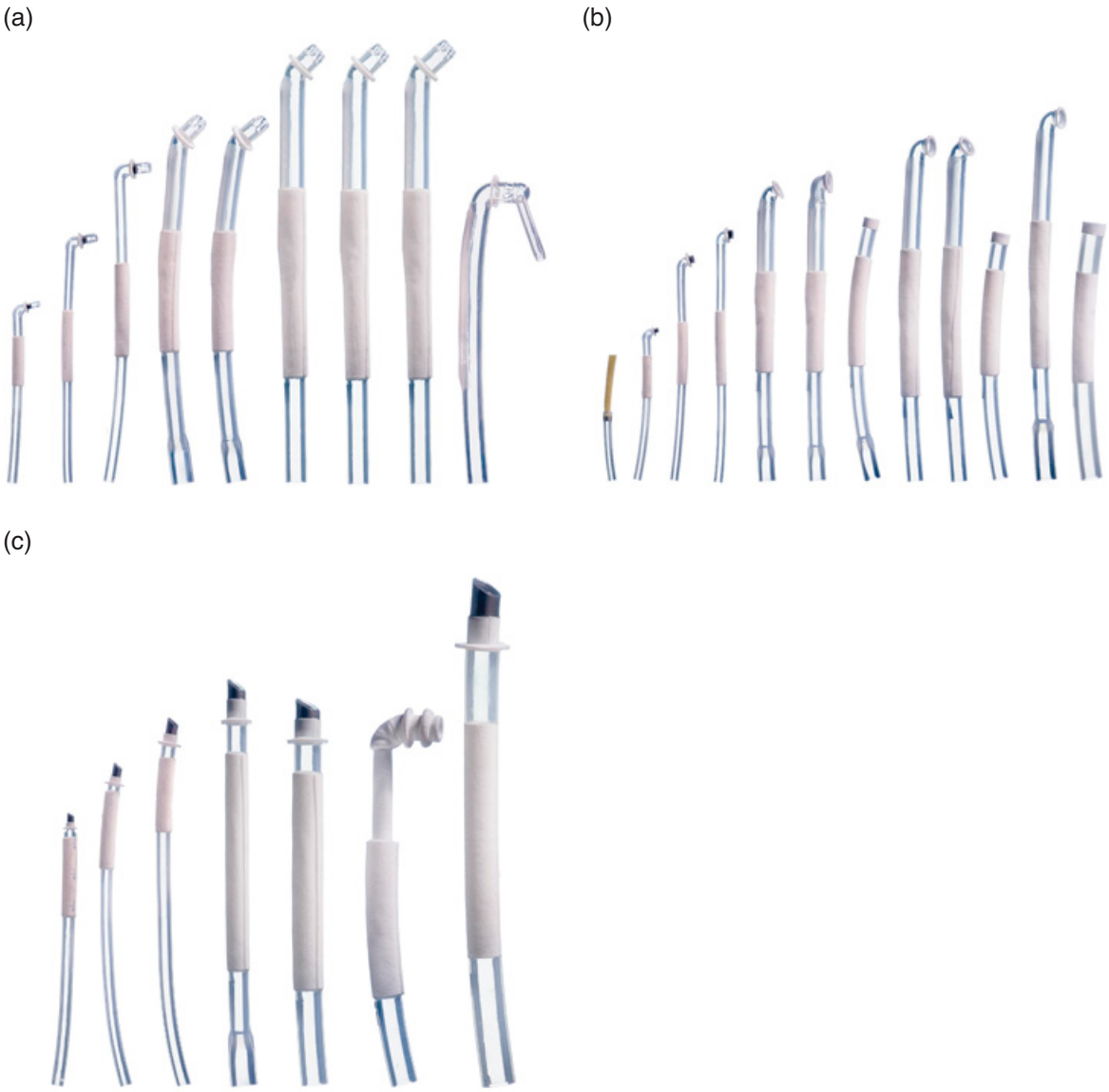

Figure 35.3 Berlin Heart cannulas. (A) Apex. (B) Arterial. (C) Atrial. Note the various angles and tip styles. Reproduced with permission of Berlin Heart Inc.

What are the challenges involved in developing pediatric VADs?

The development of suitable VADs for children is complicated by the large surface area to volume ratio of pediatric patients in comparison to adults, lower flow velocities (increasing risk of thrombosis), narrow cannulas/connections (increasing potential for hemolysis), and the other engineering challenges of miniaturization. The application of adult-sized devices to children is inherently complicated by size mismatch, especially with smaller patients. With three-dimensional modeling and "virtual implantation" to test for fit, devices can be used successfully in patients considerably smaller than licensed indications.

What are the indications for placement of a VAD?

The need for mechanical circulatory support (MCS) arises when medical therapy has been exhausted in the setting of heart failure. The purpose of a VAD such as the Berlin Heart EXCOR is to assume or augment ventricular function and restore cardiac output and adequate perfusion to

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end-organs. The device unloads the ventricle, thereby decreasing wall stress and optimizing chances for myocardial recovery and remodeling. Ventricular assist devices have been placed in children with myocardial disease (e.g., cardiomyopathy, myocarditis) or after failed palliation of congenital heart disease. They have also been implanted when it has not been possible to separate from temporary MCS such as cardiopulmonary bypass or extracorporeal membrane oxygenation (ECMO). Generally, especially in younger pediatric patients, the VAD serves as a bridge therapy, either to transplantation or to recovery. Rarely is destination therapy an aim in this patient population, although with certain devices, it is possible for patients to be discharged home to await transplantation.

What are the outcomes for children after placement of a BH?

In the early years after introduction of the BH, higher mortality was reported in patients weighing <5 kg, with congenital heart disease, transitioned from ECMO, or requiring biventricular support. Recent outcome studies now suggest that these are no longer risk factors. This device is most commonly placed as a bridge-to-transplantation. Following transplantation, contemporary series show that children bridged with a BH have similar survival, infection, and rejection rates compared to those not requiring MCS. Although earlier patients fared less well, since 2013 children in the BH prospective registry have enjoyed survival rates in excess of 70%.

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Anesthetic Implications

What is the likely health status of a child with a BH?

In the early period after BH placement, children still experience the typical sequelae of their preceding advanced heart failure. These sequelae include chronically increased catecholamine release, down-regulation of β- and α_2-adrenoreceptors, increased pulmonary vascular resistance (PVR), poor nutritional status, renal and hepatic impairment, and fluid overload. There can also be consequences of prolonged critical care support such as ventilator-associated lung injury, challenging vascular access, line-associated thrombi or infections, dependence on or tolerance to opioids and other sedative/analgesic agents, or even stroke (particularly following ECMO). Over time, restitution of excellent tissue perfusion will hopefully ameliorate many of these issues.

Arterial thromboembolism is the most feared complication of the BH. Implantation has been associated with a 28% incidence of neurologic complications (notably ischemic stroke) and major bleeding occurs in 50% of patients. Although infectious complications, including fungal infection of the BH itself, have been reported in 86.7% of BH patients, they are not believed to contribute to mortality. Also, for patients supported only with a BH LVAD, it is very common for a degree of pulmonary hypertension to develop as a result of left atrial hypertension, even if the underlying cardiac pathology is predominantly left-sided.

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What medications are typically taken by children with a BH?

Anticoagulation is invariably required by BH patients. Clinicians are challenged by the proverbial "tightrope" between bleeding and clotting risks. The Edmonton Anticoagulation and Platelet Inhibition Protocol was developed from early European experience with the device and forms the basis of most protocols in use. Protocols are typically institution specific and modified based on each center's own experiences. Standardly utilized drugs include an unfractionated heparin infusion initiated early postoperatively after bleeding has settled, followed by aspirin, enoxaparin or warfarin, and dipyridamole. The use of the newer direct thrombin inhibitor bivalirudin, instead of heparin, in the early postimplantation period is increasing. Clopidogrel is often added as well. High-dose steroids may be administered, particularly for the prothrombotic state that accompanies an inflammatory response in the absence of infection.

Anticoagulant effectiveness is generally monitored using laboratory testing of anti-Xa activity, often along with prothrombin time, thromboelastography (TEG), platelet mapping, and similar tests. Higher doses of anticoagulants are occasionally required compared to dosages typically employed for other indications. In many centers, either a multidisciplinary group or one or two designated physicians manage anticoagulation for BH patients. It is imperative that

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these individuals are involved in perioperative decision making. A hematologist may additionally be consulted.

Berlin Heart patients with long intensive care unit (ICU) courses are also frequently on weaning regimens of methadone, benzodiazepines, clonidine, and other similar sedatives.

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For which procedures are children with a BH most likely to need anesthesia care?

Given the poor chronic health of many BH recipients, along with the need for early anticoagulation, the need to provide anesthesia for surgical control of early postoperative bleeding is only to be expected. In these situations, patients are likely to still be mechanically ventilated. Surgical reexploration is often performed at bedside in the ICU, thus avoiding the hazards of transport.

The BH pumping chamber may need to be changed out for traumatic damage or clot burden. As this procedure can be performed within a matter of seconds, a single bolus of a sedative agent will likely suffice, unless high urgency and a full stomach necessitate protection of the airway with rapid sequence intubation.

In view of the need for administration of multiple medications and frequent blood draws, vascular access placement is one of the most commonly performed procedures in children with a BH. Peripherally inserted central catheter (PICC) line insertion typically requires a relatively cooperative child, but the use of anxiolytic medications and local anesthesia often suffice as there is minimal pain or hemodynamic disturbance. Insertion of a tunneled central line, however, usually requires general anesthesia.

Diagnostic imaging may also require sedation or anesthesia. Procedures may be brief (such as a brain computed tomography [CT] scan for workup of stroke) or more involved, such as a cardiac catheterization for pretransplant evaluation or evaluation of PVR.

A thorough analysis must be conducted of the potential risks and benefits when any procedure is proposed for a BH patient. In some cases, procedures are better deferred until after device explantation. At other times, indications are so overwhelming that surgery must proceed. These cases often include diagnostic or therapeutic endoscopy, interventional radiology procedures for gastrointestinal bleeding, surgical airway evaluation, and laparotomy for ischemic bowel.

In the adult VAD literature, laparoscopic cholecystectomy has been reported, as VAD-associated chronic hemolysis may lead to cholelithiasis. This seems unlikely in children for whom the BH is used as a bridge to transplantation but may be relevant for any child with a different type of VAD being utilized for long-term or "destination" therapy.

Orthotopic cardiac transplantation is the expected outcome for most BH patients. Anesthesia considerations are standard as utilized for re-do median sternotomy, and heavy blood loss is expected in view of the therapeutic coagulopathy.

What anesthetic considerations exist for this patient and how do they impact the anesthesia plan?

Given the patient's low hematocrit, he should be transfused prior to the procedure with 15–20 mL/kg of packed red blood cells. This is important in restoring preload for this patient. An intravenous induction with either etomidate (0.2–0.3 mg/kg) or ketamine (1–2 mg/kg) and rocuronium (0.6–1.2 mg/kg) should provide good conditions for endotracheal intubation. Maintenance with sevoflurane should be well tolerated, but volatile agents should be titrated to account for loss of systemic vascular tone and possible resulting hypotension. In the event of hypotension, a fluid bolus of 10 mL/kg is a reasonable first-line therapeutic intervention, followed by phenylephrine boluses (1 mcg/kg initially) to address vascular tone issues.

Finally, in view of their often complicated preceding ICU course, long-term inpatient status, and the challenges of living on a VAD, these patients often have high anxiety about any procedure, especially those requiring anesthesia. Furthermore, many of these patients have developed a significant tolerance to sedatives and analgesics.

Clinical Pearl

Berlin Heart pre-anesthesia check:

- *Hematologic plan discussed and understood by surgeon/proceduralist, VAD team +/– hematology, blood bank, intensivist, and anesthesiologist*
- *Current hemoglobin/hematocrit, coagulation panel, TEG, and other relevant labs reviewed*
- *Protamine, heparin, and mirror (for observing filling and ejection of the BH chamber) available*
- *Anti-siphon valves on any existing central vascular access lines (and precautions if placing new lines)*
- *VAD team/perfusionist contact details readily available*

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What complications might be anticipated during anesthesia for a child with a BH?

Malignant dysrhythmias

In the event of "cardiac arrest" rhythms (such as ventricular fibrillation or tachycardia), the continuous pumping of the BH should ensure that cardiac output is maintained. Indeed, even if the right heart is unsupported, passive pulmonary perfusion should be sufficient in the short term. The manufacturer cautions that external cardiac compressions should not be performed as they risk trauma to the cannulas or their anastomoses. However, there are case reports of prolonged chest compressions without damage. In general, dysrhythmias should receive standard therapy including electrical cardioversion if necessary, although this may require anesthesia rather than sedation, as cerebral perfusion is maintained by the VAD and thus consciousness is maintained during malignant dysrhythmias.

Sudden loss of VAD output

Loss of device output may be heralded by loss of consciousness in the awake patient, interruption to the normal sounds emitted by the BH device, or an alarm signal from the driver unit. In parallel with checking the status of the patient, it is essential to ensure that the compressor hose has not become kinked, which is a common problem in the mobile child. It can also result from the movements of the operating table or personnel. Air leak is also possible and certainly should be considered after resolution of a kinked hose. Although the BH drive unit has a battery backup, prolonged loss of electricity can lead to loss of VAD output. A hand pump is kept with the drive unit for this type of emergency and for catastrophic mechanical failure of the drive unit itself.

Inadvertent cannula disconnection or brisk leakage of blood from a cannula necessitates clamping of the cannulas, disconnection of the compressor hose, and urgent summoning of both cardiac surgeon and perfusionist. Actual or impending embolism of a large clot or the appearance of air in the chamber (air embolism) requires a similar approach.

Sudden cyanosis

In addition to the usual causes of cyanosis, pulmonary embolism must be considered in patients with either an RVAD or poor native right heart contractility. Cyanosis may also result from right-to-left shunt through a previously unrecognized patent foramen ovale or atrial septal defect, which can occur when VAD-assisted left heart output exceeds pulmonary venous return. Echocardiography will reveal this complication. A change in VAD programming to raise left atrial pressure above right atrial pressure should eliminate the shunt. Intravenous fluid boluses may be required.

Clinical Pearl

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What special precautions are necessary for a child with a BH?

In view of the complexity in dealing with BH patients, and the substantial individual history associated with each patient, the importance of having the appropriate VAD physician and a perfusionist both fully informed in advance of any procedure and immediately available cannot be overemphasized. In times of crisis, the ICU team is a valuable resource. When not emergent, cases should be scheduled at times when personnel and resources are immediately available.

Management of the BH device

The presence of a BH-trained nurse or perfusionist throughout the perioperative period is necessary. Although some institutions do not insist on the immediate presence of a perfusionist, it is desirable that such an individual be available within the facility for immediate consultation. Transfer of the patient and associated equipment to the operating room must be organized and efficient, as the driver battery has a finite capacity.

Great care must be taken during manual handling, such as transferring the patient to the operating table. Damage to or disconnection of components is possible and life threatening. Clear sterile drapes should be placed over all paracorporeal BH components during surgery so that visual confirmation of function and filling remains possible. Alcohol-based antiseptic solutions and radiant heaters may damage the chamber.

Clinical Pearl

Monitoring BH chamber status: *Clear sterile drapes should be placed over all paracorporeal BH components during surgery so that visual confirmation of function and filling remains possible. Filling and ejection of the BH chamber is best observed using a mirror to view the undersurface of the chamber. Look for irregularities in the smooth surface of the membrane at the end of filling or ejection to show that the preceding phase has not been fully completed. A little less than full filling is ideal, signifying that the upstream venous*

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pool is adequately decompressed. Specifically, in the case of an LVAD, this reflects an absence of pulmonary venous congestion. In the case of ejection, however, it is desirable that all of the blood in the chamber is expelled, as incomplete emptying risks thrombosis.

Hematologic Considerations

The effects of multimodal anticoagulation and the necessity for its continuation must be appreciated. A TEG may be useful to demonstrate the effects of therapy. For some surgeries, temporary conversion from warfarin or low molecular weight heparin to an unfractionated heparin infusion is indicated. This would allow anticoagulation to be withheld for a short time perioperatively. A typical approach would be to stop the heparin drip 2 hours before surgery, and then to resume it an hour after hemostasis is achieved. Any use of vitamin K must be discussed with the VAD team and hematology colleagues, as it may prevent the immediate effective postprocedural use of warfarin. Both heparin and protamine should be available in the operating room. Packed red blood cell and platelet transfusions may be necessary, and it should be anticipated that significant coagulopathy can exist. Regional anesthesia is generally contraindicated due to anticoagulation.

Hemodynamic Considerations

Either intravenous or volatile induction agents are generally well tolerated as the supported ventricle is not susceptible to their negative inotropic effects, but since the BH system offers no compensation for any drop in systemic vascular resistance (SVR), fluid boluses or α-receptor agonists may be required for treatment of hypotension, especially during induction. A lower incidence of hypotension has been reported with ketamine compared to other induction agents. If substantial fluid shifts are likely, invasive hemodynamic monitoring is appropriate. Transesophageal echocardiogram (TEE) is useful if major cardiovascular instability is encountered. Principles for hemodynamic management are listed below.

- As fixed VAD output is the major hemodynamic concern, maintaining circulating volume is of prime importance.
- Minimize PVR, especially if the right heart is not supported by a device.
- Spontaneous ventilation may maintain better systemic venous return than positive pressure ventilation but risks pulmonary hypertensive crisis in susceptible patients when considering the respiratory depressive effects of the vast majority of sedatives/anesthetics.
- In patients with only LVAD support, if the procedure is major or the patient is unstable, right heart support may be necessary, so inhaled nitric oxide (iNO) and an epinephrine infusion (beginning at a low dose of 0.02–0.04 mcg/kg/minute) should be available.

Elevations in SVR risk stasis and thrombosis, so excellent analgesia should be provided. Although remifentanil has been used in adult VAD patients undergoing surgery, its use has not been reported in children with a BH; it can lead to bradycardia and hence insufficient venous return in cases where the left but not the right heart is being supported.

Infection Control

Antibacterial prophylaxis should be agreed upon in advance and should include antistaphylococcal coverage where appropriate, although published guidance on this aspect of care is not readily available.

Clinical Pearl

Occasionally, for LVAD patients, if the procedure is major or the patient is unstable, right heart support may be necessary. Inhaled nitric oxide and an epinephrine infusion (start at low dose 0.02–0.04 mcg/kg/minute) should be available.

What considerations exist when placing invasive lines in a patient with a BH?

In the case of right heart support with a BH, there is considerable risk of air entrainment during attempted central line placement, as the VAD generates negative pressure to fill its chamber. During puncture of great veins, some centers change the programming to decrease suction on the RVAD until the inserted catheter is closed to the atmosphere, at which point VAD settings are restored.

Furthermore, when placing a central venous line in any patient with BH RVAD, great care must be taken to avoid damage to the chamber inlet valve, embolism, or thrombus. Anti-siphon valves are advisable on infusions running through central lines in cases of RVAD or BiVAD support, as the BH may generate back pressure.

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What is the appropriate disposition for a BH patient after anesthesia?

Due to the complexity of anticoagulation management for BH patients, these patients must remain in the hospital. Postimplantation, patients are recovered in the ICU, but as their overall health status improves, they can be transitioned to stepdown or floor status, depending on the institutionally driven comfort level of the staff. Following major surgery, the patient should return to the ICU. For minor procedures, return from the post-anesthesia care unit to a high-dependency environment is reasonable. In this patient's case, provided the procedure is uneventful, return to the cardiac stepdown unit would be appropriate.

Suggested Reading

Cave D. A., Fry K. M., and Buchholz H. Anesthesia for noncardiac procedures for children with a Berlin Heart EXCOR Pediatric Ventricular Assist Device: a case series. *Paediatr Anaesth* 2010; **20**: 647–59.

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