Anesthesia for Ventricular Assist Device Implantation

Ventricular assist devices (VADs) are medical devices that are used to support the patient with either acute or chronic cardiac decompensation. Most often, these devices are implanted as temporary “bridges” to recovery or transplantation (BTT) [1]. Less commonly, they are implanted permanently as “destination therapy” (DT) [2].

Ventricular assist devices are classified based on a number of characteristics, including location of the device itself, the method by which they support the circulation and the extent to which they require anticoagulation. Devices can be located outside the body (extracorporeal), inside the patient (intracorporeal), or immediately adjacent to the body (paracorporeal). They can be further sub-classified according to the type of blood flow provided (pulsatile or non-pulsatile/axial), driving power utilized (pneumatic or electric), or according to the level of anticoagulation required (low – anti-platelet agents only vs. full – anti-platelet agents, warfarin and/or heparin).

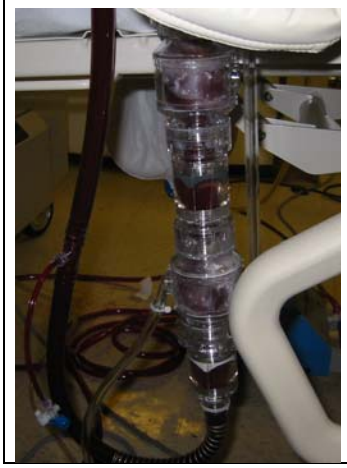
Three generations of VADs are currently available for clinical application. Some are FDA approved for therapy, while some can only be used as part of a clinical trial. The first generation generally consists of pumps such as the Thoratec VAD® or HeartMate®, which provide pulsatile flow. The second generation comprises smaller devices making use of electromechanical impellers to drive blood forward (e.g., HeartMate II®, Jarvik 2000®). The newest, third generation devices are an upgrade of the previous technologies and utilize new technology, including bearingless, magnetically- and/or hydrodynamically suspended impellers that minimize heat generation and improve durability.

Indications for LVAD implantation include end-stage heart failure and cardiogenic shock of various etiologies. After implantation, many patients experience improvement in oxygen delivery to tissues, reversal of end-organ dysfunction, increased exercise tolerance, and improved survival. Preoperative risk factors that are predictive of worse outcome after LVAD implantation include preexisiting poor renal function, right heart failure, liver dysfunction, coagulopathy and reoperation.

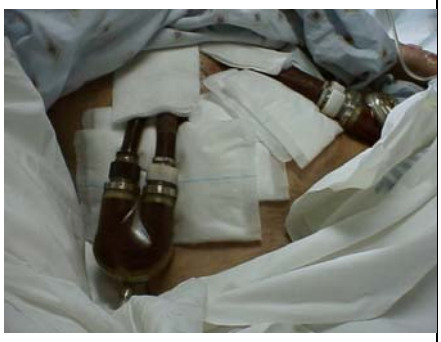
Anesthetic management during weaning from CPB and transition to VAD support or direct placement of a VAD requires an understanding of the patient’s physiologic abnormalities, intensive continuous hemodynamic monitoring, cautious administration of anesthesia agents and initiation of positive pressure ventilation, and knowledge of the device to be used and its impact on clinical management. For the anesthetic management of patients who already have an LVAD, we provide a selection of articles in the references section [3, 4].

Overview of Ventricular Assist Devices, Total Artificial Hearts, and VAD physiology

There are a number of different mechanical assist devices that are placed in patients with acute or chronic heart failure. A complete review of all of these devices, their advantages, disadvantages, indications and anesthetic implications is beyond the scope of this manual. The following tables (1-4) will briefly review some of the more commonly used devices. The types of devices used vary widely from center to center and from clinical situation to situation, so the anesthesiologist should be aware of the devices commonly used in the institution. Since information in this section may rapidly become outdated as new devices are introduced or approved, it is critical to regularly review information about the devices and their application. See the references section for articles [5, 6] that review information on currently available ventricular assist devices.

Table 1. Extracorporeal devices				
	Pump mechanism & flow type	**Configuration, special features**	**Anticoagulation**	**Approval status/clinical use**
TandemHeart® (CardiacAssist, Inc. Pittsburgh, PA) [1] 	Centrifugal	• Percutaneous left atrial to femoral arterial VAD • Venous drainage cannula (VAD inflow) is placed in LA via a trans-septal puncture • Designed for rapid deployment (within 30 mins)	Full	Approved for short-term circulatory support
Abiomed® BVS® 5000 (Abiomed Inc., Danvers, MA) 	Dual chamber, pneumatic. Pulsatile flow	• LVAD, RVAD or BiVAD. • The VAD consists of 2 chambers: an upper atrium that fills by gravity, and a lower pneumatically-driven ventricle. • An external console can support one or two VADs. It compensates for changes in both preload and afterload. • After deployment, chest remains "open", which increases infection risk and limits the use of the device. • The device functions only in "volume" mode – emptying occurs only after the ventricular chamber is full.	Full	Approved for postcardiotomy bridge to recovery or to a longer-term VAD

[1] Image from: http://www.cardiacassist.com/downloads/

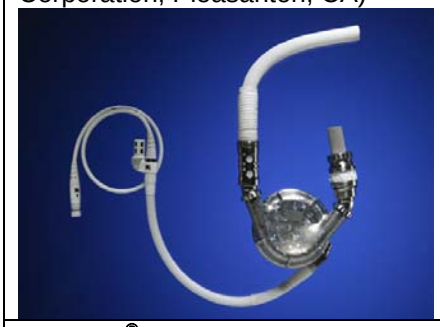
Table 2. Paracorporeal devices				
	Pump mechanism & flow type	**Configuration, special features**	**Anticoagulation**	**Approval status/clinical use**
Thoratec VAD® (Thoratec Corporation, Pleasanton, CA) 	Pneumatic – pulsatile flow	• LVAD, RVAD or BiVAD. • Can be driven by a large stationary console or a smaller portable one. Filling is largely passive and depends on an adequate CVP (>13). • Two pumping modes: **asynchronous or "fixed" mode**, where the VAD rate and ejection time are set by the user and the driver maintains those conditions indefinitely; and **volume or "auto" mode**, where ejection begins as soon as complete VAD filling occurs.	Full	FDA approved for BTT and post-cardiotomy recovery
Berlin Heart® EXCOR® and EXCOR® Pediatric[2] (Berlin Heart, Inc., Northborough, MA) 	Pneumatic – pulsatile flow	• LVAD, RVAD or BiVAD • Stationary and portable driving units available • Pediatric sizes available with 10, 25, 30, 50 or 60 ml displacement	Full	IDE approval by FDA; EXCOR pediatric trial ongoing

[2] Original image on: http://www.berlinheart.com/englisch/medpro/excor-pediatric/pumpen/

Table 3. Intracorporeal devices				
	Pump mechanism & flow type	**Configuration, special features**	**Anticoagulation**	**Approval status/clinical use**
IMPELLA® LP2.5 and LP5.0 (Abiomed Inc., Danvers, MA) [3] 	Helical propeller – axial flow	• Minimally-invasive, percutaneous catheter LVADs (2.5 and 5 l/min, respectively). • Insertion is similar to an IABP but device rests across the aortic valve, with the tip in the LV cavity.	Full	FDA approved for investigational use; FDA safety trial completed; clinical scenarios include support for patients during high-risk PCI, post PCI, and with AMI with low cardiac output (Impella® LP2.5), and postcardiotomy, myocarditis, cardiogenic shock, and bridge-to-next-decision (Impella® LP5.0)
Thoratec IVAD™ (Thoratec Corporation, Pleasanton, CA) [4] 	Implanted pneumatic – pulsatile flow	• Implantable (or paracorporeal) successor to the Thoratec VAD®. Identical operation principle. • Can be implanted in LVAD, RVAD or BiVAD configuration.	Full	FDA approved for BTT and post-cardiotomy recovery.

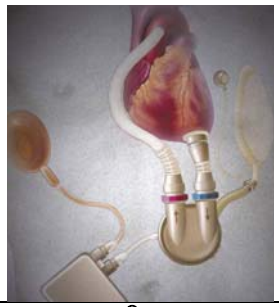
[3] Original image on: http://news.bbc.co.uk/1/hi/health/3980263.stm

[4] Reprinted with permission from Thoratec Corporation: http://www.thoratec.com//news/image_catalogue.htm

HeartMate® IP (Thoratec Corporation, Pleasanton, CA) [1] 	Implanted pneumatic – pulsatile flow	• LVAD only. • Antithrombogenic inner surface composed of sintered titanium microspheres • Only device that uses low-level anticoagulation. • Like the Thoratec VAD®, these devices have two pumping modes. In the **fixed mode**, the device ejects at a preset rate (between 50 and 120 bpm) regardless of the degree of filling of its blood chamber, i.e., stroke volume varies. SV will depend on the rate of filling ("preload") of the device. • In **auto mode**, it only ejects when the chamber is 96% full, i.e. SV remains fixed at 76ml, but the rate varies. Auto rate mode maximizes the amount of blood pumped by the system and is responsive to circulatory demand.	Low-level	FDA approved for BTT and post-cardiotomy recovery.
HeartMate® XVE LVAS (Thoratec Corporation, Pleasanton, CA) [5] 	Extended lead vented electric – pulsatile flow	• LVAD only. • Antithrombogenic inner surface composed of sintered titanium microspheres • Only device that uses low-level anticoagulation. • Only device approved for DT in the U.S. • Driveline connects to an external, wearable controller and battery, allowing the patient to ambulate.	Low-level	FDA approved for BTT and DT
Novacor® LVAS (World Heart Inc., Oakland, CA) [6] 	Electric dual pusher plate – pulsatile flow	• LVAD only.	Full	FDA approved for BTT; destination trial ongoing

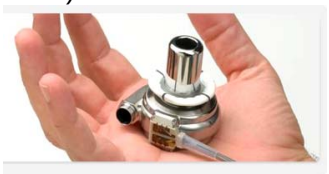
[5] Reprinted with permission from Thoratec Corporation: http://www.thoratec.com//news/image_catalogue.htm

[6] Original image on: http://www.worldheart.com/products/index.cfm

Arrow LionHeart™ (Arrow International Inc., Reading, PA) 	Pusher plate – pulsatile flow	• Totally implantable LVAD • TETS (Transcutaneous Energy Transmission System) • Operates in full-to-empty mode (fixed stroke volume) • Asynchronous with native heart	Full	Clinical trials, destination
HeartMate® II (Thoratec Corporation, Pleasanton, CA)[7] 	Impeller pump – axial flow		Full	FDA approved for investigational use; clinical trials ongoing
Jarvik 2000 FlowMaker® (Jarvik heart, Inc., New York, NY) 	Impeller pump – axial flow	• Can be implanted though a left thoracotomy [7] • Smallest 2nd generation LVAD • External, wearable lithium battery can provide 8-10 hours of operation	Full	Clinical trial for DT ongoing, destination/bridge
DeBakey VAD® (MicroMed Cardiovascular Inc., Houston, TX) [8] 	Impeller pump – axial flow	• The inducer-impeller uses a patented ceramic bearing system • Has a flow probe for real-time direct flow measurement • Reduced surgical time compared to 1st generation LVADs due to smaller size • Virtually silent	Full	FDA approval for investigational use; clinical trials for BTT/DT use ongoing

[7] Reprinted with permission from Thoratec Corporation: http://www.thoratec.com//news/image_catalogue.htm

[8] Original image on: http://www.micromedtech.com/products2.html

HeartMate® III (Thoratec Corporation, Pleasanton, CA)[9] 	Centrifugal		Full	Preclinical trials, destination/bridge
HeartWare HVAD™ (HeartWare Ltd., Sydney, Australia; formerly Kriton) [10] 	Centrifugal pump with a single, bearingless impeller	• Implantable in the pericardium	Full	Clinical trial in Europe/Australia ongoing, U.S. IDE pending; destination/BTT
Ventrassist™ LVAD (Ventracor Inc., Foster City, CA) [11] 	Centrifugal pump with a single, bearingless impeller		Full	Approved in Europe and Australia; U.S. clinical trials ongoing; destination/BTT
Berlin Heart® INCOR® LVAD (Berlin Heart, Inc., Northborough, MA)[12] 	Bearingless impeller pump – axial flow	• Can detect residual LV pulsatility and reduce pump RPM to allow for LV filling and ejection (and minimize "suction" phenomena)	Full	

[9] Reprinted with permission from Thoratec Corporation: http://www.thoratec.com//news/image_catalogue.htm

[10] Image used with the permission of HeartWare Ltd., Sydney, Australia. Original image on: http://www.heartware.com.au/IRM/content/usa/media_images.html

[11] Picture from http://www.ventracor.com/ventrassist/ventassist_downloads.asp

[12] Original image on: http://www.berlinheart.com/englisch/patienten/INCOR/das_system/

Table 4. Total Artificial Hearts				
	Pump mechanism & flow type	**Configuration, special features**	**Anticoagulation**	**Approval status/clinical use**
CardioWest™temporary Total Artificial Heart (SynCardia Systems Inc., Tucson, AZ) [13] 	Biventricular, pneumatic, pulsatile pump	• The successor to the Jarvik 7 heart • Biventricular support (TAH) • Highest bridge-to-transplant rate (79%) of all approved BTT devices [1]	Full	Approved as BTT in patients who are in need of biventricular support
AbioCor® (Abiomed Inc., Danvers, MA) 	Hydraulically coupled, asynchronous	• Biventricular support (TAH) • Fully implantable, with a TET (transcutaneous energy transmission) system • Next generation AbioCor® II is under development.	Full	FDA Humanitarian Device Exemption approval

Criteria for LVAD placement

Following is a list of inclusion and exclusion criteria for the placement of LVADs as a BTT. (From Oz et al., 1995 [8], Mancini et al., 2005 [6])

Table 5. Current Guidelines for the Placement of LVAD as a Bridge to Transplantation

Inclusion criteria

1. Patient is a transplantation candidate
2. Systolic blood pressure <80 mmHg with either:

[13] Original image on: http://www.syncardia.com/

	Cardiac index <2.0 L/min/m^2 or
	Pulmonary capillary wedge _20 mmHg
Exclusion criteria	
1. Technical considerations	
	Body surface area <1.5 m2
	Aortic insufficiency
	Right-to-left shunt
	Abdominal aortic aneurysm
	Prosthetic valves
	Left ventricular thrombus
2. Severe right-sided heart failure	
3. Factors increasing the risk of perioperative complications	
	Right atrial pressure >16 mm Hg
	Prothrombin time >16 s
	Cardiac reoperation
	White blood count >15,000/dL
	Urine output <30 ml/h
	Mechanically ventilated patient
	Temperature >101.5°F

Columbia Presbyterian Criteria for LVAD Destination Therapy Patients. Shown without modification from Mancini et al., 2005 [6]. (WITHOUT permission.)

Table 6. Columbia Presbyterian Criteria for LVAD Destination Therapy Patients

Inclusion criteria	
	Class IIIB or IV CHF
	Inotrope dependent (failed ≥1 attempt at weaning, i.e., documented hypotension, end-organ failure, refractory CHF with downtitration)
	Maximal medical therapy with VO_2 <10 mL/kg/min (if not able to tolerate β-blockers, then VO_2 <12 mL/kg/min)
Exclusion criteria	
	Transplantation candidates
	Acute cardiogenic shock
	Renal dysfunction: dialysis, CVVH, or Cr >3 mg/dL
	Hepatic failure: ALT, AST >3 times normal, INR >2.5
	BMI <18 or >35 kg/m^2
	Prolonged ventilatory support
	FEV_1 <1
	PVR >8 and/or severe RV dysfunction with anticipated RV support
	Comorbidity with life expectancy <2y
	Acute condition: GI bleed, infection
	Neurological: Mini Mental Exam score <20, prior CVA with significant residual
	High surgical risk (ascending aortic carotid artery, >2 prior cardiac surgeries)
	Severe PVD (limb ulcers, amputation)
	Heparin-induced thrombocytopenia
	Psychosocial factors

CVVH indicates continuous venovenous hemofiltration; Cr, creatinine; ALT, alanine transaminase; AST,

aspartase transaminase; INR, international normalized ratio; BMI, body mass index; PVR, pressure-volume relationship; RV, right ventricular; GI, gastrointestinal; CVA, cerebrovascular accident; and PVD, peripheral vascular disease.

VAD Physiology

For left ventricular support, blood is drained from the left atrium or left ventricular apex to the pump and returned to the patient via the ascending aorta. For right ventricular (RV) support, blood is drained from the right atrium or RV to the pump and returned to the main pulmonary artery. For example, in the HeartMate® XVE, blood enters the pump through an inflow cannula that is sutured into the apex of the left ventricle. One-way valves ensure that the blood exits the device via the outflow cannula during device systole. The outflow cannula is anastomosed end-to-side to the ascending aorta. In most cases, the device assumes most of the work of the LV and delivers the majority of the total cardiac output into the ascending aorta.

Although devices from different manufacturers use differing strategies to accumulate and eject blood, the principles of VAD function are similar. In most cases, VADs are operated in an automatic (variable) rate, fixed volume mode (a.k.a. “full-to-empty” mode). In the variable-rate/fixed-volume mode, the pump will automatically eject as soon as the pump chamber is full (also see Table 3 for a description of these operating modes). Decreased pump output can be due to patient and mechanical factors that result in excessively slow or incomplete pump filling or in prolonged or incomplete pump emptying. The two most important factors leading to decreased pump output are **hypovolemia** and **increased afterload**.

Left ventricular assist devices will support the left ventricle. When the LVAD is used alone, the right ventricle has to do all its own work. Therefore, it is critical to avoid pulmonary hypertension (excess RV afterload) and avoid volume overload (excess RV preload), both of which can precipitate right ventricular failure when only a LVAD is placed. Central venous pressure and TEE monitoring is very important to assess RV function during weaning from CPB. With chronic LVAD therapy, the reduction in LVEDP will translate into reduced RV afterload. Therefore, over time even poor RVs improve in the presence of a well-functioning LVAD.

Anesthetic management for VAD implantation

For a more detailed discussion, please see a selection of review articles [3, 9-11] in the references section.

Preoperative considerations

- Patients who are having an LVAD implanted have, by definition, severely compromised LV function. The fact that the patient is presenting for VAD implantation suggests that a further decompensation has occurred. One should attempt to determine the possible causes of the decompensation: pneumonia, sepsis, arrhythmias, or myocardial ischemia.
- Serum electrolytes can be abnormal, often in association with chronic diuretic therapy.
- There is frequently elevated pulmonary vascular resistance, impaired RV function,

impaired hepatic function and/or coagulopathy, renal insufficiency and reduced response to catecholamines.
- Patients may be on multiple inotropes, IABP, and/or a ventilator.
- Blood products should be available (packed red blood cells, FFP, and frequently also platelets may be required).
- Note the PA pressure, pulmonary vascular resistance and cardiac output. If available, obtain cardiac catheterization data, paying special attention to the transpulmonary gradient, PVR and response to pulmonary vasodilators.
- Note the most recent echocardiography report with specific reference to RV failure, tricuspid regurgitation and/or pulmonary hypertension.
- Antibiotic prophylaxis should be given (e.g. vancomycin 1 gm and cefuroxime 1.5 gm). Check with local protocol whether antifungal prophylaxis should also be administered. Fungal infections are known to occur with VADs [12, 13].

Transport to OR

- Transport the patient to the operating room with appropriate monitoring (this will usually include ECG, arterial line, pulse oximetry).
- The patient should breathe oxygen-enriched air.
- Continue all inotropes; do not alter the existing inotropic regimen.
- If the patient is already on sedation, continue the same regimen.
- If transporting an intubated, ventilated patient, strive to maintain minute ventilation, FiO_2 and PEEP requirements established in the ICU. Seemingly small alterations may lead to significant instability.

Lines and monitors

- Large-bore venous access.
- Arterial line.
- Transesophageal echocardiography.
- Central venous catheter(s): #9 French introducer with a pulmonary artery catheter; PAC introducer and/or second CVC.
- Continuous cardiac output monitoring has been studied prospectively in 15 HeartMate® recipients [14]. The CCO system overestimated cardiac output by approximately 500 mL/min when compared with the LVAD-reported flow values. The use of CCO monitoring with a PAC is therefore not recommended where a reliable VAD flow reading is available (HeartMate®, Abiomed®).
- An oximetric PAC can be useful.

Intraoperative Management

- If the patient has an internal cardioverter-defibrillator (ICD), then its defibrillator function needs to be turned off to prevent inadvertent discharge.
- Induction techniques should be selected to avoid myocardial depression. Hypotension is a major risk during induction in this patient population. Keep in mind that any agent intended to counteract hypotension will take significantly longer to take effect due to slow circulation time [15].
- Rapid sequence induction with avoidance of positive pressure mask ventilation is

generally not used, in order to minimize periods of apnea and the ensuing hypercarbia. The latter may increase PVR and further decrease left ventricular filling. Instead, maintenance of ventilation is recommended [11].
- Administer adequate amnestics.
- Aprotinin has been often used. Familiarize yourself with institutional and surgeon practice. As in other cardiac surgeries, for maximum safety it is suggested to administer the aprotinin test dose after heparinization and aortic cannulation, lest an anaphylactic reaction ensues that requires immediate institution of CPB.
- There is some evidence to support vitamin K infusion IV throughout the case at 2 mg/hour for reduction of bleeding [16]. This, however, is not practiced in all centers.
- Typical operating room ventilators may not permit NO administration. Check with the perfusion department or whoever manages the NO equipment at your institution and make adequate preparations.
- Full systemic heparinization is mandatory. Suggested initial dose is 300 units/kg. Maintain ACT about 4 x baseline.
- Full CPB is used but the aorta is not cross-clamped and cardioplegia is not needed.
- Prepare milrinone, norepinephrine, and vasopressin.
- Epinephrine, nitroglycerin, magnesium, and other typical resuscitation drugs should be available.
- Insulin may be required to maintain normoglycemia.

Separation from CPB and post-CPB period

Important goals for separation from CPB include:
- Inotropic support of the RV
- RV afterload reduction, with NO if necessary. Due to its delivery only to ventilated areas of lung, NO has the added benefit of improving ventilation/perfusion matching and P_AO_2 [11]. A favorable response to NO therapy will be manifest as increased LVAD flow and a reduction in CVP. Nitric oxide causes suppression of nitric oxide synthase expression within hours, causing NO dependency to develop. It should therefore never be weaned quickly except in patients who were non-responders initially. In the latter group, it will add no benefit and should be discontinued promptly.
- Vasoconstrictors may be necessary to maintain systemic arterial blood pressure.

Monitor for, and manage:
- Right ventricular (RV) failure
- Coagulopathy and hemorrhage
- Hypovolemia, inadequate urine output
- Inadequate ventilation, oxygenation, acidosis and hypothermia
- Altered VAD performance (low VAD flow).

TEE exam

Please refer to the reference section for review articles on this topic [17, 18].

Pre-CPB:

- Check for a **patent foramen ovale, atrial septal defect or ventricular septal defect.** An unrecognized**,** untreated intracardiac shunt can lead to unexpected hypoxemia in the post-CPB period. Unless the right-to-left communication is obvious

on color flow Doppler or regular imaging, an intravenous bubble contrast study is recommended.

- One should to detect and quantify **aortic insufficiency**. Regurgitant flow through the AV will cause recirculation through an LVAD and poor systemic perfusion. Therefore, an incompetent AV should be oversewn or replaced. The magnitude of recirculation can be estimated by the difference between a thermodilution cardiac output measurement (RV CO) and the LVAD flow measured (or calculated) by the LVAD console.
- The remaining valves ought to be evaluated with particular attention paid to **mitral stenosis** and **tricuspid regurgitation.**
- **Right ventricular function** should be assessed.
- Examine the cardiac chambers for **thrombus.**
- Check for **aortic atheromata.**

On CPB and post-CPB:

- Ensure adequate deairing. Look for air when the device is being primed or connected. Any air that reaches the sinuses of Valsalva may enter the RCA ostium. A sufficient amount of air entering the RCA will cause ischemia, which can present as sudden RV decompensation. The treatment consists of maintenance of adequate coronary perfusion pressure and resting the heart on CPB until no air persists in the RCA.
- Evaluate inlet cannula position and blood flow velocity by CW Doppler (inlet velocity >2.5 m/s is abnormal). There are several reports in the literature of malpositioned [19] or even completely reversed [20] LVAD cannulae, leading to disastrous hemodynamic consequences. In both cases referenced here, the cannula malpositioning was diagnosed using TEE, allowing corrective surgical measures to be taken.
- Recheck for patent foramen ovale. LA decompression and bowing of the interatrial septum to the left as a consequence of the LVAD may unmask a PFO that could not be detected on the pre-CPB study. It is important that this be done before protamine administration in order to avoid the need for reheparinization.
- Confirm proper LVAD function by evaluating LV decompression, aortic valve closure during LVAD systole, and outlet cannula presence in the aorta with appropriate flow.

Management of RV Failure

RV failure is a relatively common but potentially disastrous complication of LVAD placement. Undiagnosed or masked preoperative biventricular failure may now become evident on termination of CPB. Right heart failure may present abruptly and be difficult to manage once it becomes severe.
Following LVAD implantation, RV failure is characterized by low LVAD flows (decreasing LVAD filling with increasing RAP), high CVP, decompressed LV and interventricular septal flattening on TEE. Pulmonary artery pressures may not necessarily be very high.

To prevent and manage RV failure:

- Systemic perfusion pressure should be supported with vasoconstrictor drugs.
- The right heart should be supported with positive inotropic drugs. Milrinone is often the drug of choice because its effect on pulmonary vascular resistance can help offload the RV.
- Maintain a fine balance between avoidance of hypovolemia (in order to ensure LVAD filling) and avoidance of right heart volume overload, especially in the setting of a

poorly diuresed patient with pre-operative CHF.

- Avoid excessive LVAD output. If the device empties the LV too vigorously or rapidly, the LV can collapse, displacing the interventricular septum towards the left ventricular cavity. This leads to RV dilation and significant tricuspid regurgitation. The inflow cannula may become obstructed leading to entrainment of air into the pump from around the sewing ring.
- With a well-functioning LVAD, ventricular arrhythmias may not lead to immediate hemodynamic collapse as in the unassisted patient. However, due to their detrimental effect on coronary perfusion and right ventricular function, they must be treated rapidly.
- Anticipate increased PVR due to blood products and protamine administration.
- Nitric oxide is frequently used to reduce pulmonary vascular resistance.
- If it appears that the above measures are insufficient to restore hemodynamic stability and proper LVAD function, a temporary RVAD may be life saving. Discuss early with the surgeon.

Coagulopathy

- Bleeding is often a problem. A prolonged duration of CPB, along with platelet activation and fibrinolysis, worsen any pre-existing coagulopathy. It is necessary to anticipate this potential problem and order sufficient blood and blood products. The coagulopathy can extend well into the post-operative period and can lead to surgical re-exploration.
- If possible, use leukocyte-filtered products to reduce the formation of reactive antibodies against blood and tissue antigens. Alloimunization will make future cross-matching of blood and a donor heart more difficult.
- Aprotinin [ibid.] has been frequently used. Epsilon aminocaproic acid can also be administered.
- Whenever feasible, transfusion therapy should be guided by PT, PTT, ACT and platelet counts. However, some studies suggest that routine coagulation tests may be misleading after VAD implantation, and alternative methods such as thromboelastography may yield more reliable information in this patient population [21].
- Recognize that transfusion can increase preload and afterload on RV.
- Normothermia should be maintained.
- Several reports indicate successful therapy with recombinant factor VIIa in VAD recipients with catastrophic bleeding, where all other measures to halt hemorrhage had failed [22, 23]. On the other hand, there is a report of a clotted-off Abiomed® BVS® 5000 device after rFVIIa administration, with a fatal outcome [24]. The use of rFVIIa is not FDA approved in this setting and cannot be recommended based on existing literature. Its humanitarian, “off-label” use in cases where all other care has failed to produce a result and death from hemorrhage seems imminent is left to the discretion of the attending clinician.

VAD Operation – notes on commonly used devices

Since each device has specific characteristics, the following provides a brief overview of some of the commonly used devices, how they operate and some recommendations for troubleshooting when they are not providing optimal hemodynamic support.

Thoratec VAD®

Monitoring:

- Flows readings on the console are not an accurate measure of flow except in the case where the VAD is emptying completely. The device assumes a 65cc stroke volume.
- VAD emptying can be assessed qualitatively by shining a light at an oblique angle along the anterior surface of the VAD and assessing the size of "light flash", which should be greater than the size of a quarter dollar.
- For the implantable Thoratec IVAD, there are pairs of LEDs that sit on top (separate) of the console that indicate whether emptying is adequate.
- Switching from asynchronous (fixed-rate) mode to volume mode will not change the proportion of time spent in systole (this is fixed at 300 msec). Therefore, decrease in heart rate with volume mode will not improve emptying (it will only improve filling). Time in systole can be changed manually to optimize filling or emptying.
- Volume mode can be used in a hypovolemic patient to ensure better filling of VAD. VAD rate will decrease in the hypovolemic patient if VAD is in volume mode until it looses its "fill" signal and switches to its fixed rate.
- Conversely, if there is inadequate emptying, VAD rate will increase in volume mode (since it takes very little time for the VAD to fill if it is not emptying).
- Mixed venous O_2 is a good monitor for overall adequacy of flow and systemic perfusion.

Improving Emptying:

- Can unload RVAD with nitric oxide
- Can unload LVAD with nitroprusside if systemic pressure is adequate
- If pharmacologic measures are not tolerated or don't work, then one can increase the driving pressure. Typically, driving pressure is set at 100 mm Hg plus systemic systolic pressure (for LVAD) or 100 mm Hg plus PA systolic pressure (for RVAD).

Improving Filling:

- Volume administration; ensure that the patient is not hypovolemic.
- The Thoratec console adds a small amount of negative pressure during the filling part of the VAD cycle, which is meant to only overcome the resistance of the filling chamber. To improve filling, one can adjust negative pressure: normally set at –20 with chest open and –40 when chest is closed. The risk of increasing negative suction is that air could be entrained around the inflow cannula insertion site, causing air embolism.

Abiomed® BVS® 5000

Monitoring:

- Flows readings on the console are accurate for the Abiomed® BVS® 5000. The console measures the volume of driving gas that is being used to displace an equal volume of blood during each systole.

Improving Emptying:

- Pharmacologic interventions are the same as with the Thoratec® VAD. Driving pressure is fixed: 320 mmHg for LVAD and 220 mmHg for RVAD.

Improving Filling:

- Lower the position of the bladder with respect to patient's body. VAD fills by gravity. Note that when bladder position is lowered, the afterload against which the VAD pumps is increased.

- DO NOT place the patient in a “head down” position while the bladders are fixed to the table.

HeartMate® LVAD

- The HeartMate® console computes LVAD flow within +/- 5% (range, 1.8 to 10 L/min).
- This device is relatively afterload-independent. The “driving pressure” is fixed.
- Inadequate preload will result in slower heart rate and drop in CO. Aim for a HR in the 70-80 range.
- High flows can lead to LV collapse with shift of the intraventricular septum towards the LV, resulting in RV dilation, increased RV wall stress, and RV failure. Therefore, fixed mode is frequently used to prevent RV failure.

Table 7. Hemodynamic effects of IABP and hemodynamic requirements of common circulatory assist devices

	IABP	Abiomed® BVS® 5000 BiVAD	Thoratec® BiVAD	HeartMate® LVAD	Abiomed® BVS® 5000 RVAD HeartMate® LVAD	Abiomed® BVS® 5000 RVAD	ECMO
Preload	*No effect*	*CVP 12-15*	*CVP > 13 recommended*	*Dependant*	*CVP 12-15*	*CVP 12-15*	*Normal*
Afterload	*IABP will reduce*	*Keep SBP<150.*	*Keep SBP<130.*	*Keep SBP<120*	*Keep MAP<100*	*Native LV*	*Normal*
Position-dependent relative to patient	*No*	*Yes: Caution with Trendelenburg*	*No*	*No*	*Yes*	*Yes*	*Requires good cannula positioning*
Effect of inotropes	*Positive*	*No effect*	*No effect*	*Use for RV support*	*No effect*	*Use for LV support and VAD weaning*	*No effect*

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