



Mechanical Cardiac Circulatory Support: an Overview of the Challenges for the Anesthetist

Andrew Notarianni¹ · Mayanka Tickoo² · Amit Bardia¹

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Abstract

Purpose of Review Owing to increased utilization of Mechanical Circulatory Support (MCS) devices, patients with these devices frequently present for surgeries requiring anesthetic support. The current article provides basics of perioperative management of these devices.

Recent Findings Use of extracorporeal membrane oxygenation (ECMO) and left ventricular assist devices (LVADs) are on the rise with recently updated management guidelines. Venovenous ECMO utilization has been widely utilized as a salvage therapy during the COVID-19 pandemic.

Summary Intra-Aortic Balloon Pumps continue to be one of the most frequently used devices after acute myocardial infarction. ECMO is utilized for pulmonary or cardiopulmonary support as salvage therapy. LVADs are used in patients with end-stage heart failure as a destination therapy or bridge to transplant. Each of these devices present with their own set of management challenges. Anesthetic management of patients with MCS devices requires a thorough understanding of underlying operating and hemodynamic principles.

Keywords Mechanical Circulatory Devices · Anesthesia · ECMO · LVAD · IABP

Introduction

Mechanical Circulatory Devices are increasingly being utilized both for acute and chronic heart failure [1•]. Patients with these devices often develop multiple complications necessitating multiple procedures/surgeries needing anesthetic support. A sound understanding of the functioning of these devices and hemodynamic goals is important for optimal care of these patients. In this review, we outline the salient features of three commonly employed MCS devices: (1) Intra-Aortic Balloon Pump (IABP), (2) Extracorporeal

Membrane Oxygenator (ECMO), and (3) Implantable Left Ventricular Assist Device (LVAD).

IABP for the Anesthesiology Provider

Intra-Aortic Balloon Pump (IABP) is one of the earliest and most frequently utilized mechanical circulatory support devices utilized for cardiovascular support. It is an endovascular catheter with a distal balloon positioned in the aorta distal to the origin of the left subclavian artery. It works on the principle of counterpulsation against intrinsic pulsatile left ventricular activity to augment the diastolic blood pressure and myocardial oxygen delivery as well as reduce myocardial oxygen demand [2]. Traditionally, the IABP has been used in acute myocardial infarction (MI), MI induced complications (e.g. mitral regurgitation or ventricular fibrillation), especially in cardiogenic shock[3]. It is also frequently used in cardiac surgery to support hemodynamics in patients undergoing coronary artery bypass graft surgery in the peri-operative setting. While IABP does not increase cardiac output significantly, especially compared to other MCS devices like ventricular assist devices, its ease of

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✉ Amit Bardia
amit.bardia@yale.edu

¹ Department of Anesthesiology, Yale School of Medicine, New Haven, CT 06515, USA

² Pulmonary and Critical Care Medicine, Department of Internal Medicine, Yale School of Medicine, New Haven, CT, USA

insertion, long-standing safety profile and improved automation highlights the high prevalence of use of this device[4]. IABP is a non-durable form of MCS and therefore, only a bridge to definitive therapy. While these patients are considered unstable and may rarely undergo general anesthesia procedures, they might require emergent minimally invasive procedures like those performed by interventional radiology or vascular procedures.

Device Configuration

The IABP comprises a double lumen catheter with a balloon at its distal end usually inserted percutaneously through the femoral artery with the tip of the catheter positioned just distal to the origin of left subclavian artery. The outer lumen of the catheter is attached to a console that drives the balloon which is usually filled with Helium (30–50 ml based on the size of device) while the inner lumen is used for invasive arterial pressure monitoring. The console is programmed to identify a “trigger” for inflation of the balloon, usually the “R” wave on EKG such that the balloon deflates at the beginning of systole (opening of aortic valve), and inflates at the beginning of diastole (closure of aortic valve, diastolic notch on arterial waveform) (Fig. 1). Alternatively, if the

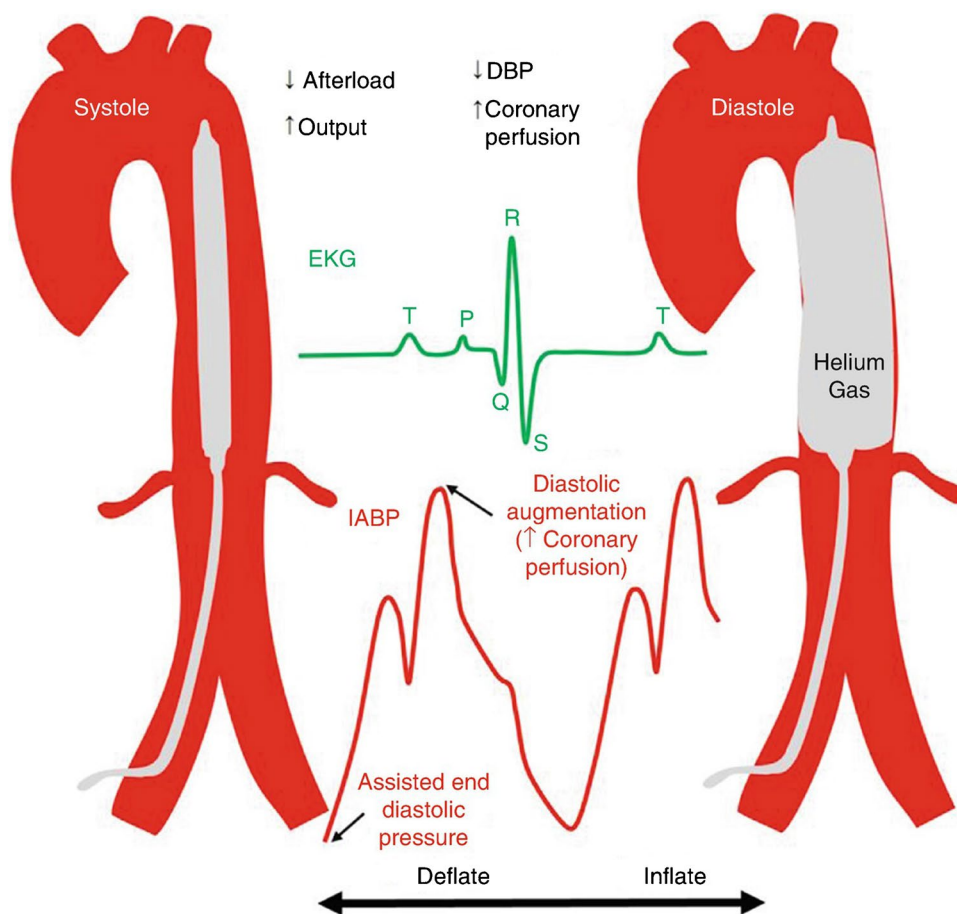
patient has an arterial line, its waveform may be utilized to trigger the balloon pump. In case of loss of pulsatility, such as during CPR, the IABP can be switched to an internal waveform trigger.

During diastolic augmentation with balloon inflation, there is augmented perfusion pressure in the coronary arteries which improves oxygen delivery to the myocardium [5]. During systole, due to a vacuum effect created by balloon deflation, there is reduction in LV afterload and cardiac work which further reduces myocardial oxygen demand and augments cardiac output.

Practical Considerations

- By virtue of augmenting the diastolic BP and lowering systolic aortic pressure, the IABP reduces cardiac work. However, the MAP remains stable, and is the hemodynamic measure to follow in a patient with an IABP.
- Ensuring precise timing is imperative to optimal functioning of the IABP. If the IABP is too slow to deflate (i.e. it deflates after during LV systole) or too early to inflate (i.e. it inflates prior to aortic valve closure), it increases the afterload on the heart and may be deleterious to hemodynamics. Similarly, if the IABP inflates well

Fig. 1 Mechanism of action of an Intra-aortic Balloon Pump [43]: the device inflates during diastole and deflates during systole. The inset shows timing of the inflation and deflation as ascertained by the arterial line tracing with respect to the EKG



after aortic valve closure or deflates well before the aortic valve opening, it would have a suboptimal benefit to the hemodynamics. Optimal functioning of the IABP should be ascertained while looking at the arterial waveform for patient-device synchrony.

- Depending on the level of compromise, IABP can be set up for augmenting every cardiac cycle (1:1 configuration; highest support) to every few cardiac cycles (1:2–1:4 configuration; lesser support) [6]. Patients with IABPs are often on systemic anticoagulation esp. with lower levels of support given the high risk of arterial thrombosis and its antecedent complications (e.g. embolic stroke).
- The position of the IABP is crucial to its optimal function. Proximal migration can compromise blood flow to the left subclavian artery and distal migration can compromise renal blood flow (manifests as hematuria) as well as arterial flow to lower extremities (weak pulses, paresthesia, pain). In addition to high clinical vigilance for these events, a chest x-ray is performed to confirm positioning of the device especially after travel/movement.
- Barring momentary pauses, the balloon should never be turned off in situ due to the high risk for thrombosis.
- The blood in the driveline indicates IABP balloon rupture. This may become a nidus for thrombi or lead to gas embolization. Heparin should be administered immediately and IABP should be expeditiously removed [7].
- During cardiac arrest CPR should be performed per AHA guidelines and the trigger may be switched to an internal mode.

ECMO for the Anesthesiology Provider

Extracorporeal life support (ELS) and mechanical oxygenation (ECMO) techniques have advanced rapidly in scope and adoption over the previous decades. Recent influenza and coronavirus pandemics have accelerated the expansion of ECMO capabilities into centers previously lacking these capabilities [8]. The contemporary anesthesia provider must now be familiar with these techniques of support and the implications for perioperative patient management.

Circuit Design

The perioperative clinician must have a thorough understanding the implications of circuit design and utilization to care for patients undergoing ELS. Two broad groups of extracorporeal support exist: the first intended to support primary respiratory failure (veno-venous ECMO – VV ECMO) and the second supporting circulatory failure with or without concurrent respiratory failure (veno-arterial ECMO – VA ECMO). Distinct cannulation strategies are necessarily

employed and have significant implications for management. In simple terms, an ELS/ECMO circuit consists of a venous drainage (inflow) cannula, a mechanical pump, a membrane lung with heat exchanger, and a return cannula (outflow) with effluent return determined by the intent of support.

Cannulation and Circuit Configuration

VV ECMO for respiratory support utilizes venous access for both affluent and effluent circuit flow. As such, all extracorporeal blood flow and gas exchange are pre-pulmonary. Gas exchange may be weaned and suspended without veno-arterial shunting as native lung function recovers. Most commonly, femoral venous drainage with internal jugular return or a dual-stage inflow-outflow (Avalon®) cannula in the internal jugular vein is employed. Recirculation may occur when oxygenated return blood is entrained back into venous drainage as both cannulae are positioned within the great veins and this may impair the oxygen delivery to the patient. As circuit flow returns to the venous system, no hemodynamic support is provided by VV ECMO. Blood flow through the lungs and systemic circulation is essentially unchanged and unsupported; standard perioperative monitoring and hemodynamic support may therefore be employed [9].

VA ECMO provides hemodynamic support in the setting of circulatory failure. Because the blood is drained from the venous system and returned to the arterial tree to support systemic blood flow, gas exchange via a membrane lung is required to prevent the delivery of de-oxygenated blood returning to the systemic circulation (veno-arterial shunt) [10]. Respiratory support is therefore necessarily also provided by VA ECMO. In contradistinction to VV ECMO, the specific blood return strategy (outflow cannula location) employed in VA ECMO is of paramount importance for peri-operative management and monitoring. In certain cases, a hybrid of VV and VA configurations has been described and employed [11].

VA ECMO strategies may be classified into two groups: central cannulation and peripheral cannulation on the basis of the location of the return of blood flow to the patient. Central cannulation is rarely encountered outside of specialized cardiac surgical care. Drainage comes from the great veins and is most often returned into the ascending aorta leading to antegrade blood flow within the arterial tree. This typically ensures the return of oxygenated blood to the aortic root and head vessels ensuring oxygen delivery to the coronary arteries, cerebral circulation, and systemic circulation [12]. Standard respiratory monitoring is adequate and hemodynamic monitoring is dictated by the overall clinical situation. The complexities of management are otherwise beyond the scope of this review.

Peripheral VA ECMO is much more likely to be encountered by the non-cardiac specialist and presents nuances that require special attention in peri-operative management. Blood return to the patient is most often via the femoral artery and venous drainage most often via femoral vein. A smaller-bore “reperfusion catheter” is often inserted just distal to the femoral arterial catheter to provide blood flow to the distal extremity in an antegrade fashion. When blood flow from the ECMO circuit is returned via the femoral artery, it is critical that the anesthesiology provider understands that extracorporeal blood flow is retrograde through the arterial tree and that admixture of blood from the native cardiopulmonary circuit and extracorporeal circuit will be present. As native cardiac output is most often very low (prompting VA ECMO support), retrograde flow is usually sufficient to ensure oxygenated blood delivery to the visceral and cerebral circulatory beds as well as to the aortic root. If native cardiac output is non-trivial or recovers during mechanical support, native pulmonary function and ventilatory support may become a relevant management concern as the increasing blood flow through the cardiopulmonary circuit is ejected by the heart into the aortic root. An important consideration is the so-called north–south or harlequin syndrome which can occur when poorly oxygenated blood ejected from the heart mixes with well oxygenated blood from the femoral ECMO cannula resulting in unequal and potentially harmful hypoxia in the proximal arterial tree. When present, this can result in coronary and cerebral hypoxia despite maximal oxygen saturation of blood returning from the membrane lung. For this reason, oxygenation is best assessed (pulse oximetry, arterial blood gas analysis) from the right upper extremity which derives blood flow from the innominate artery which is most proximate to the heart and furthest from the ECMO return cannula. Arterial desaturation at this site should prompt reassessment of native cardiac output in addition to ECMO flow and oxygenator function [13••].

Management

Principles of Gas Exchange and Oxygen Delivery

Gas exchange in the membrane lung is accomplished by the flow of sweep gas through a semi-permeable membrane, the so-called membrane lung. Sweep gas is derived from a wall source with tank back-up. A flowmeter allows for the titration of sweep gas flow and therefore ventilation via the ECMO circuit. Adjusting the sweep gas flow is analogous to changing alveolar minute ventilation. Manipulation of the sweep flow within typical gas and pump flows will result in a mostly linear alteration in arterial carbon dioxide tension. An oxygen blending knob allows for the titration of

the fraction of oxygen delivered to the membrane lung and may be used to titrate the delivery of oxygen to the artificial lung. Adjustment and management of oxygen delivery are much more complex than that of ventilation. The amount of oxygen delivered by the ECMO circuit depends on the rate of blood flow through the circuit, the increase in oxygen saturation of hemoglobin across the membrane lung, and the hemoglobin concentration in accordance with the oxygen content and delivery equations [14]. Blood flow back to the patient typically has an oxygen saturation of high 90 s–100% (with normal oxygenator function) but actual arterial oxygen saturation will be determined by the ratio of oxygenated ECMO blood flow to total native blood flow and oxygen saturation. During VV ECMO support, mild hypoxemia is generally tolerated given the above physiology and a saturation in the high 90 s% is not expected until lung recovery is present. Focus is often placed on maintaining oxygen delivery by maintaining a pre-oxygenator O₂ saturation of greater than 70%, which may be considered a surrogate of MVO₂ in this setting [15]. Augmenting hemoglobin concentration with transfusion is employed frequently to maintain oxygen-carrying capacity and delivery. A perfusionist or respiratory therapist ECMO team member will be available to assist in the adjustment of flow parameters as needed.

Hemodynamic Management

Owing to the non-pulsatile flow of VA ECMO, mean arterial pressures (MAPS) are commonly utilized for blood pressure monitoring. MAP goals of > 70 are preferred for patients with VA ECMO [16••]. Additionally, in order to prevent LV thrombosis from stagnant blood, a strategy for LV emptying is employed, often by either placing a surgical LV vent or by using inotropic support to augment LV ejection and aortic valve opening (represented by the presence of dicrotic notch on the arterial line tracing) [17]. Serial ABGs are performed to preclude North–South syndrome. Serial serum lactate is often trended to rule out the presence of gut or limb ischemia. Due to the large distribution volume and drug sequestration by ECMO membrane, larger doses of pharmacologic support may be required to achieve desired drug effect [18].

Ventilatory Management

Lung protective ventilation is recommended during ECMO support. Multiple trials have explored the ideal ventilation strategy but no clear optimum has been established [13••] Maintenance of recruitment, avoidance of toxic concentrations of FiO₂ (> 0.6), and minimization of driving pressures are currently recommended. Many centers prefer pressure-controlled strategies. Because ventilation is quite effective via the circuit, high minute volumes are seldom necessary.

Tracheostomy is a commonly performed procedure patients and gas exchange via the circuit can provide a margin of reserve during this procedure [13••].

Anticoagulation

Anticoagulation is indicated during ECMO support but controversy exists regarding the optimal agent and intensity [19]. Most centers utilize unfractionated heparin with a PTT target of greater than 2 × normal. Monitoring by anti-Xa level and use of direct thrombin inhibition is also common. Bleeding complications are frequent and often require temporary suspension of anti-coagulation and transfusion. There is some evidence to suggest that VV ECMO may continue without systemic anti-coagulation however thrombotic complications are of particular concern in a VA configuration due to the potential for arterial embolization [20]. The oxygenator should be checked frequently for evidence of fibrin formation and may require oxygenator exchange. Limb ischemia distal to the arterial return cannula can result in serious limb threat with or without anti-coagulation. Operative intervention for compartment syndrome or acute ischemic limb threat is a frequent peri-operative presentation. There is no consensus in regard to timing or need to hold anticoagulation for surgical procedures. This decision should be guided based on the nature of the surgery with multidisciplinary discussion.

LVADS for an Anesthesiology Provider

Implantable Left Ventricular Assist Devices are increasingly being used as a salvage therapy for patients with end-stage heart failure as a destination therapy or a bridge to transplant [21•]. This is in part driven by their improved survival rates over time [22]. With the tremendous increase in LVAD utilization and improved survival over time, it is extremely likely that these patients will increasingly present for non-cardiac procedures. Patients with LVADs commonly undergo GI procedures, vascular procedures, have strokes

which may need neuro-intervention procedures, and often need emergent surgeries for acute causes [23, 24]. A sound understanding of the intricacies and hemodynamic goals is thus imperative while managing these patients.

Device Configuration

Currently, most of the devices that are being implanted are continuous flow devices with HVAD and HeartMate III being the most common ones being utilized [25, 26]. These devices consist of an inflow cannula which is inserted into the LV cavity, a pump which is placed in the pericardial space and an outflow cannula which returns the blood to the ascending Aorta [27, 28]. The blood is drawn from the left ventricular cavity and is pumped by the impeller into the ascending aorta via the outflow cannula in a non-pulsatile fashion by a centrifugal pump. Common hemodynamic parameters utilized to describe LVAD functioning are mentioned in Table 1.

Hemodynamic Considerations

Optimal functioning of the implantable LVADs require adequate right ventricular (RV) function to accomplish LV filling which allows preload for the LVAD to pump blood across to the ascending aorta. Etiologies leading up to heart failure (esp. non ischemic heart failure) often affect both the ventricles. LV offloading by the LVAD often unmasks impaired RV function and often puts additional stress on the RV to keep up with LVAD output [29••]. Additionally, long-standing heart failure may result in elevation of Pulmonary Vascular Resistance (PVR) which in turn acts as a detriment to RV function. Moreover, enhanced decompression of the LV cavity by the LVAD flows often moves the interventricular septum away from the midline further stressing the RV output as the RV is heavily dependent on the septum for generating cardiac output.

Management of patients with LVADs therefore revolves around supporting the RV function. Important considerations include minimizing RV dilatation by avoiding volume

Table 1 Parameters used to describe LVAD mechanics

Parameter (unit)	Significance
Speed (rpms)	It is the speed by which the impeller spins to propel blood across into the outflow cannula
Power (W)	It is the measure of the current and voltage applied to the LVAD
Flow (l/min)	It is the blood flow propelled by the LVAD pump. It is determined by the speed, the viscosity of blood, and the pressure differential between the inflow and outflow cannula
Pulsatility index (dimensionless)	It signifies differential flow across the LVAD during systole and diastole. It is calculated by the formula: $PI = \frac{Q_{max} - Q_{min}}{Q_{Avg}}$ where PI = Pulsatility index, Q_{max} = maximum flow during systole, Q_{min} = minimum flow during diastole, and Q_{Avg} = average flow during cardiac cycle

overload, adding inotropes (such as epinephrine, milrinone), and decreasing afterload via pulmonary vasodilators such as inhaled NO.

Severe decompensation of RV function may lead to an increase in RV size as it fails to generate forward flow and a concomitant decrease in the LV cavity size due to unloading of the LV by the LVAD. In extreme cases, this decrease in the LV cavity size may lead to the septum come in contact with the LV inflow cannula which may cause ventricular arrhythmia. Management of these events would include defibrillation, decreasing the pump speed to allow for LV filling and adding inotropes to augment RV output [30].

Due to non-pulsatile flow of the latest generation LVADs, mean arterial pressure (MAPs), rather than a systolic and a diastolic pressure, is monitored to ensure adequate perfusion pressure. A goal MAP of greater than 65–70 is usually considered adequate. High MAPs are associated with higher afterload leading to decreased pump output and have been shown to be associated with pump thrombosis and strokes esp. with HVADs [31, 32]. Similarly, low MAPs esp. less than 55 have been linked to end-organ injury.

Perioperative Management

Important considerations for patients with LVAD undergoing procedures are mentioned in this section. The type of procedure/surgery, the urgency (emergent/non-emergent), and patient's physiological status often dictate the perioperative management.

Preoperative Consideration

It is recommended that the anesthetic team contact the center's LVAD coordinator if time allows it for LVAD evaluation prior to the surgery. A thorough patient history should include assessment of any recent decompensation of the patient's cardiopulmonary status, strokes, and anticoagulant regimen. Preoperative physical exam should include assessment of JVD and pedal edema as these may indicate decompensated RV function. Recent investigations especially transthoracic echo may provide useful information about the RV function. These patients are often on anticoagulants which may require cessation of anticoagulants or emergent reversal using four-factor prothrombin complex concentrate (4F-PCC) depending on the nature and urgency of the surgery [33, 34]. Furthermore, as these patients are prone to intraoperative bleeding, it may be prudent to have an active type and cross depending on the type of planned procedure. Patients with LVADs often have implanted AICDs, which may require interrogation prior to surgery as recommended by current guidelines for perioperative management of AICDs [35].

Intraoperative Considerations

Intraoperative monitoring utilizing standard ASA monitors is recommended for patients with implantable LVADs. Given the non-pulsatile flow generated by the centrifugal devices, monitoring of MAP utilizing an arterial line is recommended as depending on automated inflated cuff pressures may be inaccurate [36]. In cases of minor planned procedures, manually acquired Doppler pressures may be a suitable alternative to placement of invasive arterial lines [37]. Additionally, due to the non-pulsatile blood flow pulse oximeters, readings may not be accurate necessitating frequent arterial blood gas measurement to ensure adequate oxygenation. If high dose pressor/inotropic support is anticipated, placement of pre-incision central venous line may be beneficial. This also allows for monitoring of CVP, an indicator of RV filling pressures. Intraoperative transesophageal echocardiography may be helpful in assessing patient's hemodynamics as it provides real-time assessment of the RV function and the position of the interventricular septum. Application of external defibrillator pads is advised in patients where AICD is turned off in anticipation of electrocautery interference.

Anesthetic induction should be performed with utmost care as it may eliminate the patient's sympathetic drive leading to hemodynamic decompensation. Judicious practices utilized during induction of patients with heart failure should be observed [38]. Vasopressin has a lesser impact on pulmonary arterial vascular resistance may be beneficial [39]. Additional attention to preserving RV function as described above is imperative while managing these patients. This includes avoidance of hypoxia, hypercarbia, and fluid overload. This may be particularly challenging in long laparoscopic procedures that are marked by high incidence of hypercarbia leading to increase in PA pressures [40]. Hyperventilation and discontinuation of pneumoperitoneum to allow for a decrease in PA pressures should be considered during episodes of recalcitrant hypotension from impaired RV function during these procedures. Transfusion with blood products should be performed especially judiciously to avoid volume overload and in patients who are awaiting heart transplants (to avoid sanitization to donor antigens). Point of care coagulation tests may be helpful in aiding decisions regarding transfusion.

Overreliance on LVAD flow displayed on the console should be avoided as it is a calculated number and may not reflect the actual cardiac output.

If faced with cardiopulmonary arrest in a patient with an LVAD, standard CPR including chest compressions should be performed per AHA guidelines [41]. Per the guidelines, the harm from withholding compressions far outweighs the risk of dislodgment of LVAD cannula. Additionally, the proper functioning of LVAD should be assessed by

listening for a hum over the left chest and left upper abdominal quadrant.

Postoperative Considerations

The anesthetic recovery of the patient should occur in a monitored environment by appropriately trained practitioners comfortable in taking care of patients with MCS devices [42]. Special considerations should be given to avoiding hypercarbia, rapid identification of postoperative bleeding and optimizing volume status. Additionally, resumption of CRT/AICD and anticoagulation should be performed judiciously following a multidisciplinary discussion.

Conclusions

With an increase in the prevalence of heart failure and a concurrent increase in the utilization of mechanical circulatory support, familiarizing oneself with the salient features of commonly employed devices is essential for anesthetic management of these patients. Additionally, knowledge about one's institutional resources and indications for placement of these devices as a salvage therapy may prove to be useful in cases of intraoperative cardiac deterioration in this growing patient population.

Declarations

Conflict of Interest The authors do not have any potential conflicts of interest to disclose.

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