Southern African Journal of Anaesthesia and Analgesia. 2021;27(6 Suppl 1):S5-10
https://doi.org/10.36303/SAJAA.2021.27.6.S1.2723

South Afr J Anaesth Analg
ISSN 2220-1181 EISSN 2220-1173

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Cardiovascular mechanical support

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Cardiovascular mechanical support includes the use of devices such as the intra-aortic balloon pump (IABP), extracorporeal membrane oxygenation (ECMO) and ventricular assist devices (VADs). These are used in cardiogenic shock (CS) as a bridge to decision (BTD), bridge to transplantation (BTT) or destination therapy (DT). CS is associated with significant morbidity and mortality.[1] It is a state of low cardiac output associated with hypotension and end-organ hypoperfusion. It includes a systolic blood pressure (SBP) < 90 mmHg or the requirement of vasopressor support to maintain an SBP of at least 90 mmHg, and some signs of end-organ hypoperfusion such as altered mental state, oliguria and a rising lactate.[2] Other advanced haemodynamic parameters include a cardiac index (CI) < 1.8 l/min/m^2 without support or < 2.2 l/min/m^2 with support and an elevated left ventricular end-diastolic pressure (LVEDP) > 18 mmHg.[2] Maximal medical therapy may no longer be seen as the end point for refractory circulatory shock, especially in well-resourced settings.[3] The goal of mechanical circulatory support (MCS) is to move blood from an insufficient ventricle into the aorta or pulmonary artery with the aim of restoring cardiac output.[4] MCS can be achieved with either short-term devices that are placed temporarily or long-term devices. It is not without complications and these need to be managed by a multidisciplinary team. The Interagency Registry for Mechanically Assisted Circulatory Support (INTERMACS) profiles are used to stratify patients with heart failure into the New York Heart Association (NYHA) functional class III or class IV into one of seven distinct profiles. Based on this profile, a practitioner is able to reasonably gauge how quickly to intervene in terms of placement of a mechanical circulatory device from hours or days to months. The American College of Cardiology/American Heart Association (ACC/AHA) guidelines recommend MCS as a class I therapy as BTT.[5]

Keywords: cardiovascular mechanical support, intra-aortic balloon pump, extracorporeal membrane oxygenation, ventricular assist devices

Introduction

Mechanical circulatory support (MCS) is used in the acute setting of myocardial infarction, myocarditis and cardiogenic shock (CS) from various causes, including postcardiotomy, as well as in chronic scenarios with advanced end-stage heart failure.[5]

Indications for MCS include the following:

- Bridge to decision (BTD) or bridge to bridge (BTB): short-term MCS is used until stabilisation of end-organ perfusion or durable support options are available.
- Bridge to transplantation (BTT): MCS such as left ventricular assist devices (LVADs) or biventricular VADs keeps a patient who is at high risk of death alive until an organ becomes available.
- Bridge to recovery (BTR): MCS such as an LVAD keeps the patient alive until the native heart function improves.
- Destination therapy (DT): long-term use of durable MCS is used in patients not otherwise eligible for transplantation.[5]

Intra-aortic balloon pump

An intra-aortic balloon pump (IABP) is one of the most commonly used mechanical assist devices in patients with CS. The device consists of a balloon mounted on a catheter usually inserted in the femoral artery, which is then positioned in the descending thoracic aorta and terminates approximately 2 cm distal to the left subclavian artery and above the renal arteries distally. The system is connected to a console that houses helium used to inflate the balloon.[6] Interestingly, the IABP-SHOCK II (intra-aortic balloon support for myocardial infarction with cardiogenic shock) trial showed that IABP use compared to medical therapy before revascularisation did not reduce the 30-day mortality in patients with acute myocardial infarction. However, relative ease of insertion and beneficial haemodynamic effects have allowed its continued use.[1]

How it works

The IABP inflates during diastole and deflates during systole. This has the effect of augmenting myocardial oxygen supply and decreasing the myocardial workload. Coronary perfusion pressure (CPP) is the difference between diastolic pressure and left ventricular diastolic pressure (LVEDP), and inflation of the balloon increases diastolic pressure and thus improves CPP and enhances blood flow. During systole, the balloon deflates and this decreases the pressure in the aorta and thus the ventricular afterload.[7] An IABP is able to improve cardiac output by 0.5–1 l/min.

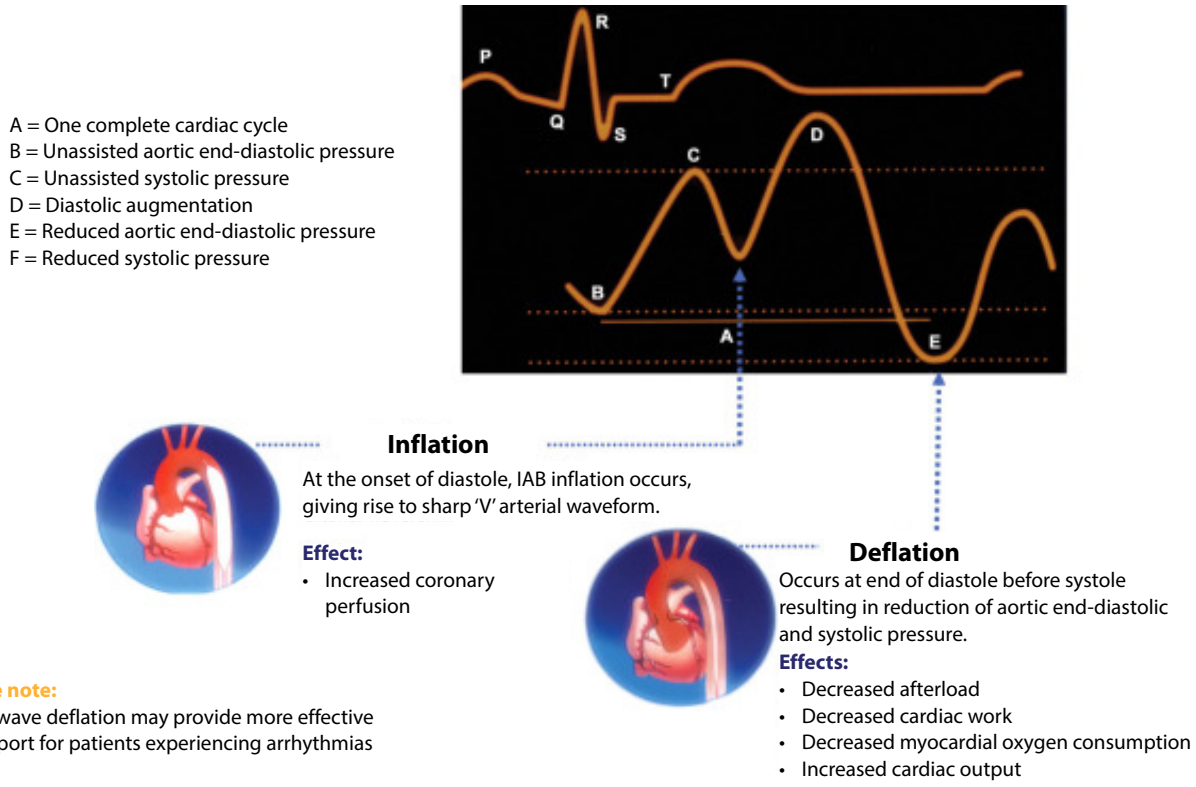

Figure 1: One complete cardiac cycle and the corresponding waveform of the IABP during inflation and deflation[1]

Optimal operation of the IABP requires inflation during aortic valve closure, on the dicrotic notch of the arterial pressure waveform and deflation before the opening of the aortic valve, as seen by the downward slope of the arterial pressure waveform in Figure 1.[7] The IABP should be programmed to use the arterial pressure waveform or the electrocardiogram (ECG) to ensure proper inflation/deflation. Improper timing of the balloon can have deleterious consequences as shown in Table I.[6]

Contraindications to the IABP include aortic regurgitation as this can worsen the magnitude of the regurgitation. It is also contraindicated in patients with aortic dissection or aneurysms as it may worsen the aneurysm or dissection. Its placement should be avoided in patients with peripheral vascular disease, and there is also a relative contraindication in those with a bleeding diathesis as anticoagulation is used in these patients. Depending on the patient's haemodynamic status, the pump can be programmed to augment every beat (1:1), or every second beat (1:2) or even less.[7]

Extracorporeal membrane oxygenation

Extracorporeal membrane oxygenation (ECMO) is derived from cardiopulmonary bypass that allows gas exchange, and in addition, circulatory support can also be provided.[8] The use of ECMO in adults was uncommon and it was mainly used in the paediatric population for respiratory failure. However, there has been a significant increase in the use of ECMO since the 2009 H1N1 influenza pandemic.[3] It can be used for a few days up to even weeks as a BTR, BTT or bridge to an implantable circulatory support.[9]

How it works

Blood is essentially moved from the venous side in venous arterial ECMO (VA ECMO), through a pump which pushes the blood through a membrane oxygenator which also removes CO_2, before the blood is returned to the patient via a warmer.[8] VA ECMO can be initiated either centrally or peripherally during peri-cardiac arrest. A large venous reservoir such as the right

Table I: Improper timing of an intra-aortic balloon pump inflation and deflation[1]

Event	Event definition	Haemodynamic consequence
Early inflation	Inflation while aortic valve is still open (before the dicrotic notch)	Increase in cardiac afterload leading to myocardial oxygen demand Premature closure of aortic valve leading to increase in LVEDP
Late deflation	Deflation after aortic valve opens (during the upslope of the arterial pressure waveform)	Cardiac ejection against an inflated balloon leads to an increase in cardiac afterload leading to myocardial oxygen demand
Early deflation	Deflation while the aortic valve is still closed (during the downslope of the arterial pressure waveform)	Early deflation leading to decrease in diastolic pressures leading to suboptimal diastolic augmentation and hence suboptimal coronary perfusion
Late inflation	Inflation after the aortic valve closes (after the dicrotic notch)	Late inflation leading to suboptimal diastolic augmentation and hence suboptimal coronary perfusion

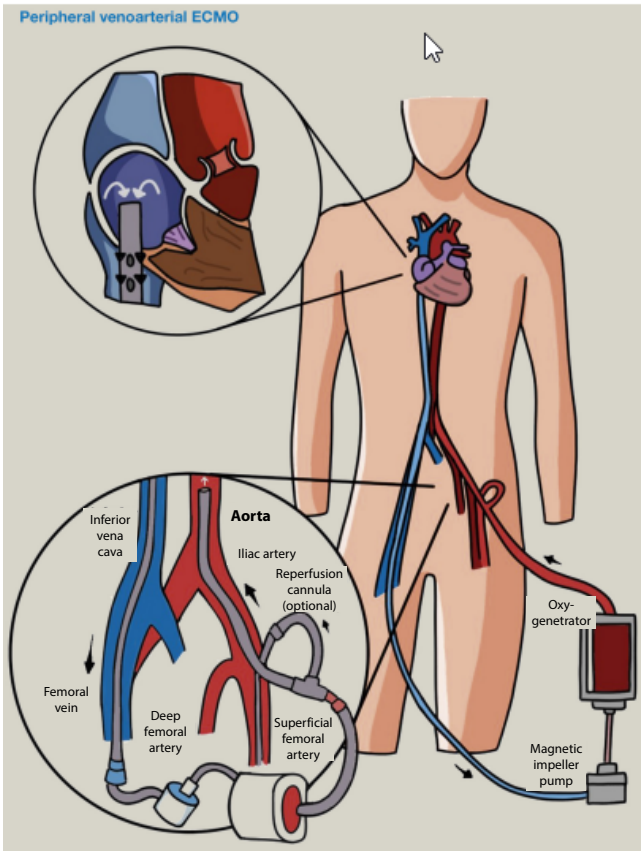

Figure 2: Peripheral VA ECMO[2]

atrium or inferior vena cava is cannulated for blood extraction and arterial return is via the aorta for central cannulation and femoral vessels for peripheral cannulation.[10] This is illustrated in Figure 2.

An ECMO circuit can be set up in essentially three ways.[8]

1. Veno-arterial ECMO which allows gas exchanges and haemodynamic support.
2. Veno-venous ECMO (VV-ECMO) which facilitates gas exchange, blood is pumped from the venous side and then pumped back into it.
3. Arterio-venous ECMO (AV ECMO) which facilitates gas exchange by using the patients' own arterial pressure to pump the blood from arterial to venous, used more for carbon dioxide extraction.

Indications for ECMO in adult cardiac failure include the following:[9]

1. Inadequate tissue perfusion manifested as hypotension
2. Persistent shock despite volume administration and inotropes
3. Typical causes are acute myocardial infarction, peripartum cardiomyopathy, postcardiotomy shock
4. Septic shock in some centres

Contraindications to ECMO use include an unrecoverable heart and if a patient is not a candidate for transplant or VAD. Other

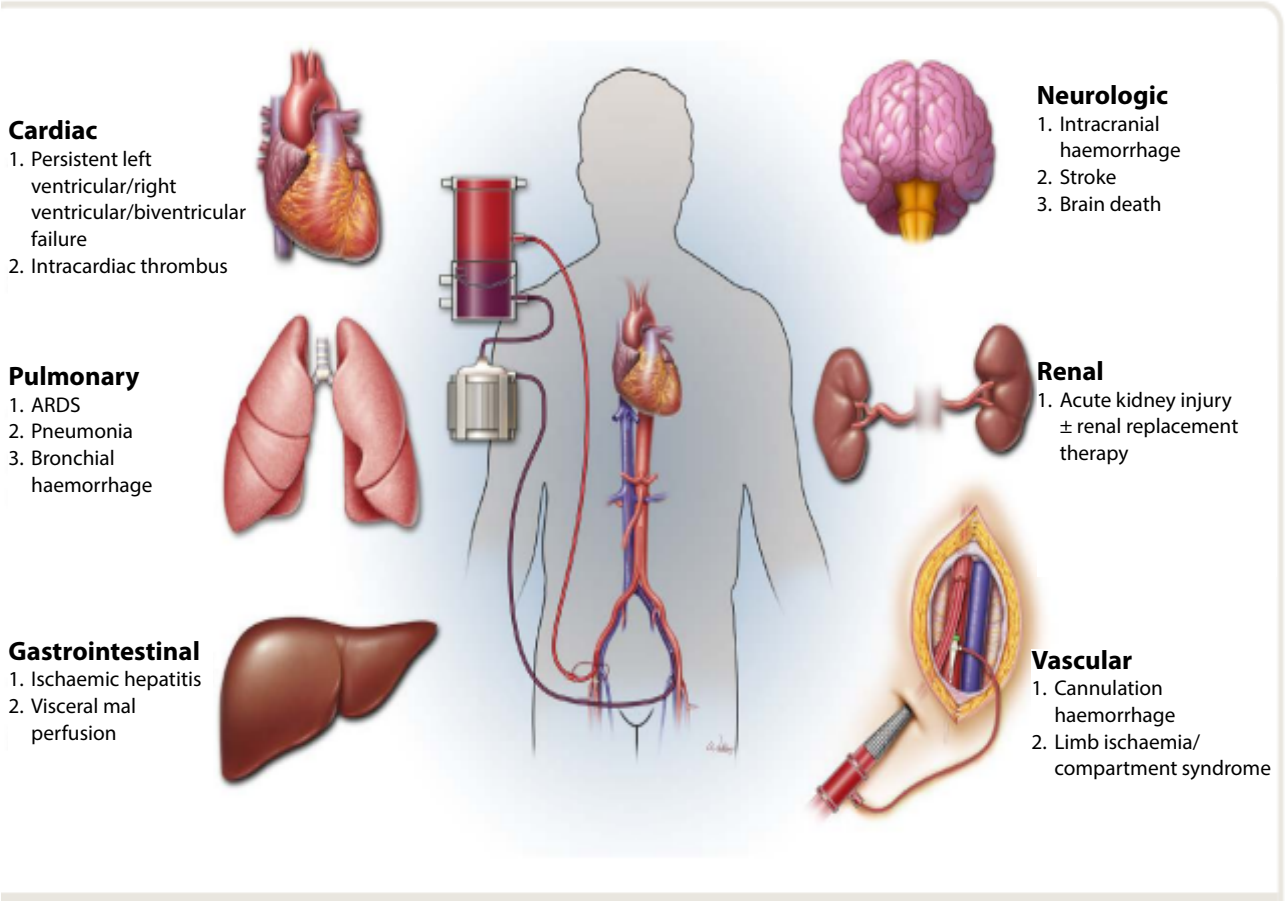

Figure 3: Major complications during ECMO according to organ systems[11]

contraindications would include chronic organ dysfunction and advanced age.

The use of ECMO can result in a rapid decrease in vasoconstrictor use. However, initially, most patients require intravascular volume expansion. Anticoagulation is essential to avoid the formation of clots in the circuit.[8] Heparin is used and the whole blood activated clotting time (ACT) is kept 1.5 times from the baseline. Thrombocytopaenia is quite common and can be multifactorial, which include causes such as heparin-induced thrombocytopaenia, sepsis or a result of the actual ECMO. Ventricular dilatation can occur due to retrograde flow in the aorta, which can further worsen myocardial damage. This is usually overcome by offloading the ventricle by inserting either an IABP or an Impella device.

Complications include bleeding, or central nervous system complications such as ischaemic or haemorrhagic stroke, as seen in Figure 3.[11] Limb ischaemia may also ensue following placement of an ECMO, the cause is multifactorial, including existing peripheral vascular disease, shock liver or coagulopathy. Distal limb cannulas may be placed to aid in limb perfusion.

Only extremely urgent surgeries should be performed in patients on ECMO. Continuous assessment of volume status, biventricular function and global perfusion should be done. Intraoperative goals are to maintain euvolaemia, biventricular contractility and adequate mean arterial pressure (MAP). Perfusion is dependent on ECMO flows and native cardiac function. ECMO flows are in turn dependent on adequate intravascular volume; therefore, any hypovolemia is to be treated promptly.[11] Weaning is encouraged with evidence of improved aortic pulsatility and cardiac contraction on echocardiography. Flows are reduced gradually to 1 l/min. Survival to discharge is 25–40%.

Ventricular assist devices

Ventricular assist devices (VAD)s can function in place of a dysfunctional left or right ventricle or both. These are essentially mechanical devices that are put in place to reduce the workload of the heart, permitting the ventricle to rest, while maintaining cardiac output and organ perfusion. These devices are often placed when medical therapy has been exhausted.[12,13] The Randomized Evaluation of Mechanical Assistance for the Treatment of Congestive Heart Failure (REMATCH) trial validated a 48% reduction in mortality among patients receiving a first-generation LVAD as opposed to optimum medical therapy.[5] VADs can be placed to provide either short-term support in acute settings or long-term support for up to years. The devices can be classified according to how blood flows through these, either pulsatile or continuous.

Continuous flow VADs include devices that can be placed percutaneously for temporary function and devices that are implanted at surgery for more long-term support.[12] Essentially, the VAD consists of an inflow mechanism to drain blood, usually from the left ventricle or left atrium for an LVAD, and an outflow mechanism to pump blood back into the arterial system such as the aorta. For the right side, blood is drained from the right atrium and pumped back into the pulmonary artery. The pump of continuous flow VADs consists of a single rotating element that imparts energy to the blood which helps to increase blood flow and pressure. These are durable as they have a single moving part.[14] Furthermore, continuous flow LVADs may be subdivided into either axial flow or centrifugal flow pumps. The main difference between these lies in the design of the rotating elements which governs how the blood flows. In an axial flow pump, the elements work like a propeller in a pipe, and in a centrifugal pump, the rotating element acts as a spinning disk with blades.[15] VADs have evolved over the years and the first-generation devices have been replaced by the second- and third-generation devices. The third-generation devices are continuous flow centrifugal pumps with a focus on smaller devices which provide less thrombosis and haemolysis.

Short-term ventricular assist devices

These include devices that are placed percutaneously, such as the Tandem heart (TH) and the Impella devices that are at best kept in for a few days. The Impella device uses an axial pump that is inserted retrogradely across the aortic valve via the femoral artery. Left ventricle (LV) blood is aspirated from the ventricle and pumped into the aorta. At least four versions of the Impella device are available and each provide a different flow rate, ranging from 2.5 l/min up to 6 l/min. An external console is attached to the catheter and allows adjustment of the pump speed to achieve the desired flow. A high speed equates to higher flows which provides better haemodynamic support. LV unloading reduces LVEDP, LV wall stress and myocardial oxygen demand. Blood flow delivered by Impella devices improves the cardiac index (CI), MAP and coronary flow.[2] Ouweneel et al.[16] showed in a randomised controlled study that the Impella device compared to an IABP as an MCS made no difference in 30-day mortality.

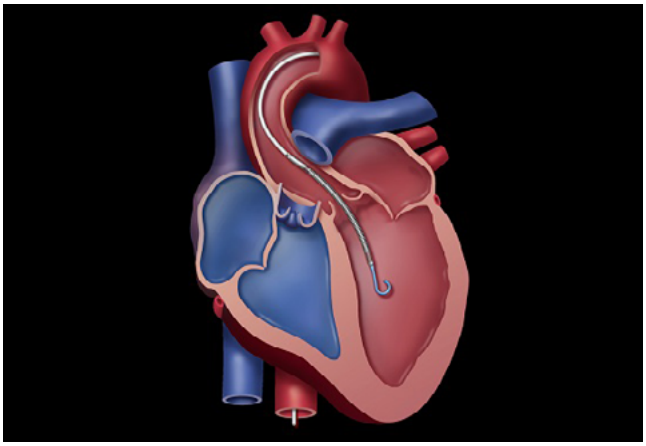

Figure 4: An Impella device draws blood from the left ventricle and pumps it into the aorta[17]

Tandem heart

This device uses a centrifugal pump to drain blood from the left atrium with a catheter placed transeptally via the femoral vein, and returns it to the femoral artery. In doing so, myocardial oxygen demand is reduced, MAP and systemic circulation all get improved. It has a console that regulates the pump, maximum speeds can reach 5 l/min. It provides superior haemodynamic support to the IABP. Despite a patient having arrhythmias or extreme tachycardia, it can continue to provide circulatory support as long as right ventricle (RV) function is satisfactory. Anticoagulation with heparin is required to prevent device thrombosis.[2]

Centrimag is another temporary VAD that can provide up to 10 l/min of flow. It includes a centrifugal pump, flow probe and console with the option of adding a membrane oxygenator. This device is surgically implanted postcardiotomy for the failing heart.[1]

Long-term ventricular assist devices

Both pulsatile and continuous flow type devices have been designed to provide long-term VAD support. Continuous flow devices are the ones most commonly used. These consist of an inflow cannula that is placed in the apex of the LV and an electrically supplied pump that draws blood from the LV, and moves it through an outflow cannula, which may be placed in the aorta. The amount of flow depends on the speed settings of the LVAD. The parameters that are shown by the device include the speed (revolutions per minute – rpm), power, pulsatility index and flow expressed in litres per minute. The pulsatility index represents the flow through the device.

There are three leading long-term LVADs on the market, namely HeartWare (Figure 5), Heartmate II and HeartMate III. HeartMate II is a second-generational axial pump weighing 281 g and it has rotational speeds of between 8 000 and 10 000 rpm. The device is implanted extrapericardially. The HeartMate III is a third-generation LVAD which is implanted intrapericardially and can produce flows of approximately 5 l/min.[6]

Figure 5: Presentation of continuous flow assist device (HeartWare)[4]
Red arrow – pump, black arrow – outflow graft, white arrow – pump cable, green arrow – battery.

In one study, 133 NYHA VI patients received a HeartMate II as a BTT.[14] After 180 days, 75% of the patients had reached the principal outcome of transplantation, recovery or survival on ongoing support with eligibility for transplantation. Patients on HeartMate II support had improvements in NYHA class, six-minute walk, functional status and quality of life.

Right ventricular assist devices (RVADs) are also available and work in the same manner as the LVADs, but RVADs mainly provide support to the right heart. Indications for placement would include right heart failure following an infarct, pulmonary hypertension, an embolus or a failing right heart after placing an LVAD.

If support is needed for both the right ventricle and left ventricle, a biventricular assist device (BiVAD) is placed. It works in the same manner as both the LVAD and RVAD. Total artificial heart (TAH) is an implantable device designated for long-term circulatory support. TAH is completely implanted in the patient. Indications for implantation would include lack of eligibility for the LVAD/BiVAD due to extensive heart damage such as a very large infarct.[4]

Complications to VADs include bleeding, thrombosis which can be catastrophic, infections, haemorrhagic or ischaemic stroke, and very rarely device malfunction.

Anaesthetic considerations for patients on ventricular assist devices

Ideally, the LVAD team should be contacted as they provide invaluable information. Again only urgent surgery should be undertaken. The type of LVAD in place, when placed and reason for placement should be obtained, as well as anticoagulation status. A recent echocardiogram can provide information especially about the RV function. Anticoagulants are not stopped if the risk of bleeding is low. Warfarin is usually bridged to heparin.[6]

Intraoperatively standard monitoring as given by American Society of Anesthesiologists guidelines is applied. Pulse oximeters may be imprecise if the pressure is low. Non-invasive pressure readings may also not be accurate. Placement of an arterial line may be difficult as some patients may not have a pulse depending on the device. Inotropic support should be available to support the RV. Other insults such as hypoxia, hypercarbia and volume overloading should be available to support the RV.

Postoperatively, patients should be monitored in a setting where staff is familiar with LVADs. Anticoagulation should be resumed as soon as possible. Adequate postoperative nausea and vomiting prophylaxis should be given to prevent increase in intrathoracic pressures and RV afterload.[6]

In an unresponsive patient who is pulseless with an LVAD and a correctly placed endotracheal tube with a CO_2 < 20 mmHg, chest compressions should be initiated. Standard cardiopulmonary resuscitation (CPR) should be instituted. The LVAD should be assessed for proper function by listening for a hum over the left chest and left upper abdominal quadrant.[6]

Conclusion

MCS provides a variety of options for patients with heart failure. It requires a multidisciplinary approach with regards to selecting the right patients at the right time and managing those patients. It is a continuously evolving field as the search for better devices with improved outcomes is sought.

Conflict of interest

The author declares no conflict of interest.

Funding source

No funding was required.

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