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An introduction to mechanical circulatory support in cardiac intensive care

Jonny Coppel[1]

Alex Rosenberg[2]

Edward Gilbert-Kawai[3]

Author details can be found at the end of this article

Correspondence to:
Jonny Coppel; jonny.coppel@gmail.com

Abstract

While use of mechanical circulatory support is increasing, knowledge of its fundamental role and limitations remains poorly understood by many medical professionals. This article summarises the main types of mechanical circulatory support and how they work, particularly focusing on the key information medical professionals should know should they encounter them in hospital. Mechanical circulatory support can be an effective treatment modality in selected pathologies, including myocardial ischaemia, pulmonary congestion, massive pulmonary embolic disease, postcardiotomy cardiogenic shock with failure to wean off bypass, right ventricular failure, bridge to heart and lung transplant and, increasingly, extracorporeal cardiopulmonary resuscitation. Intra-aortic balloon pumps increase coronary perfusion and reduce myocardial oxygen demand in a variety of cardiac conditions. Extracorporeal membrane oxygenation can provide both respiratory and circulatory support to patients. Ventricular assist devices can provide support for not only patients with acute cardiogenic shock, but also for ambulant patients in the community setting.

Key words: Extracorporeal membrane oxygenation; Intra-aortic balloon pumps; Mechanical circulatory support; Ventricular assist devices

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Introduction

The use of mechanical circulatory support is on the rise, and as such it is essential that doctors of all specialties in the hospital setting have a basic understanding of its function and limitations. At the most basic level, the predominant physiological role of mechanical circulatory support is perhaps best thought of as a means to offload the strain on the heart. More specifically, mechanical circulatory support serves to reduce cardiac filling pressures, left ventricle volumes, myocardial wall stress and oxygen consumption, while at the same time increasing coronary perfusion and systemic oxygen delivery (Rihal et al, 2015). In providing a period of relative organ support, mechanical circulatory support has therefore been used to treat a variety of pathologies, including cardiogenic shock, pulmonary congestion and myocardial ischaemia (Krishna and Zacharowski, 2009; Martinez and Vuylsteke, 2012; Harris and Kuppurao, 2012).

The first potential use of mechanical circulatory support was described by Kantrowitz (1953), who demonstrated that slowing down the arterial pressure pulse of anaesthetised dogs led to an increase in coronary blood flow. Two decades later, the first purpose-built mechanical circulatory support device was developed in the form of an intra-aortic balloon pump; subsequently, extracorporeal membrane oxygenation and the ventricular assist device have been introduced. These different devices, which are individually discussed in more detail below, have several overlapping indications – the choice of which device to use depends on the individual pathophysiology and patient characteristics, as well as the local expertise and available facilities. In some instances, simultaneous use of two different types of mechanical circulatory support in tandem may be indicated, for example using an intra-aortic balloon pump or short-term ventricular assist device to avoid left ventricular distension in patients receiving veno-arterial extracorporeal membrane oxygenation.

Notably, while the use of mechanical circulatory support has burgeoned, the supporting evidence for their implementation has been mixed. In the seminal 2012 IABP-SHOCK II article (Thiele et al, 2012), intra-aortic balloon pumps were not shown to reduce 30-day mortality in patients post-myocardial infarction who had cardiogenic shock.

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Although in need of further validation, some later studies indicate that they may benefit specific subgroups of patients; for example, in one study a lower 30-day mortality was demonstrated in patients with cardiogenic shock secondary to myocardial infarction in whom percutaneous coronary intervention was unsuccessful – although a higher mortality risk was seen in those in whom percutaneous coronary intervention was successful (Hawranek et al, 2018). In a second study, higher starting central venous pressures and lower heart rates were predictors for significant haemodynamic response to intra-aortic balloon pumps in patients with decompensated heart failure (Imamura et al, 2018). When intra-aortic balloon pumps have been compared to ventricular assist devices, a meta-analysis showed that ventricular assist devices (in the form of an Impella device), significantly improved parameters of shock severity and left ventricular fraction, but offered no significant difference in 30-day mortality compared to an intra-aortic balloon pump (O'Neill et al, 2012). The subsequent post-myocardial infarction cardiogenic shock IMPRESS trial (Ouwennel et al, 2017) found the same effect on mortality. Despite the mixed supporting evidence, mechanical circulatory support is included in the European Society of Cardiology guidelines for patients with post-myocardial infarction cardiogenic shock (Ibanez et al, 2018).

In terms of the data supporting the use of extracorporeal membrane oxygenation, the CESAR trial (Peek et al, 2009), undertaken during the H1N1 epidemic, demonstrated an increased survival at 6 months without significant disability in patients transferred to extracorporeal membrane oxygenation-capable respiratory failure centres. Additionally, the optimum timing of extracorporeal membrane oxygenation use in patients with acute respiratory distress syndrome is still unclear, as demonstrated by the EOLIA trial (Combes et al, 2018) that showed no significant difference in 60-day mortality if extracorporeal membrane oxygenation was used early in acute respiratory distress syndrome compared to using standard mechanical ventilatory strategies, including extracorporeal membrane oxygenation, if patients developed severe hypoxaemia. So, while veno-venous extracorporeal membrane oxygenation is now considered part of the standard treatment for severe acute respiratory distress syndrome alongside established hospital networks that ensure the highest quality of care, no large-scale trials have been performed investigating the benefits of venous-arterial extracorporeal membrane oxygenation, although a number of trials are ongoing such as EUROSHOCK (NCT03813134). Additionally, the use of veno-arterial extracorporeal membrane oxygenation in cardiopulmonary resuscitation is becoming more widespread and is a subject of ongoing research (Pappalardo and Montisci, 2017).

Despite the paucity of data, which may in part be a result of the difficulties in carrying out large-scale research on a heterogeneous group of very unwell patients in the relatively few centres that have the expertise to use these devices, the indications for implementation of mechanical circulatory support continue to advance as more reliable and durable devices are developed, and as a greater understanding is gained of some of the major determinants of mechanical circulatory support success (eg patient selection, preoperative optimisation and the timing of implantation).

Three mechanical circulatory support devices are discussed in further detail below: intra-aortic balloon pump, ventricular assist devices and extracorporeal membrane oxygenation. Table 1 outlines their respective indications and contraindications, and Table 2 their complications.

Intra-aortic balloon pump

What is the device?

The intra-aortic balloon pump consists of a balloon, a pump and an electronic console that inflates and deflates the helium-filled balloon at the correct times. The balloon, which is situated at the end of a small catheter, is inserted percutaneously (usually through the femoral artery), to sit in the aorta just distal to the root of the left subclavian artery. The catheter has two lumens – a central one that connects to the transducer and monitors the intra-aortic pressures, and another in the outer lumen which is used to transmit gas to the balloon.

Table 1. Indications and contraindications

Device	Indications and uses		Contraindications
Intra-aortic balloon pump	■ Bridging patients with acute cardiogenic shock to recovery or surgery, for example a. Post-myocardial infarction b. Post-myocardial infarction ventricular ectopy refractory to pharmacological therapy c. Bridging patients until surgery or percutaneous coronary intervention d. Weaning patients off bypass machines e. Cardiomyopathy or myocarditis-related ventricular failure ■ Intractable angina ■ Severe haemorrhage from aorta or its branches		■ Significant aortic aneurysms or dissection ■ Significant aortic regurgitation ■ Uncontrolled sepsis ■ Uncontrolled bleeding disorders ■ Severe unstented peripheral artery disease ■ End stage cardiac disease except as bridging tool
Ventricular assist devices	Short-term devices	Bridging patients with acute cardiogenic shock to recovery or surgery as above	■ Significant aortic regurgitation ■ Mitral stenosis ■ Intracardiac shunts ■ Left ventricular thrombi ■ Significant aortic aneurysm or dissection ■ Recent or evolving strokes ■ Irreversible hepatic or renal failure ■ Metastatic cancer
	Medium–long-term devices	Bridging heart failure patients to: a. Transplant or at least decision to transplant b. Recovery* (very rare use in the UK) ■ Destination therapy†	
Extracorporeal membrane oxygenation	Veno-venous	Conditions where the lungs are unable to perform gas exchange but cardiac output is still sufficient to perfuse the systemic circulation, for example ■ Severe pneumonia ■ Acute respiratory distress syndrome ■ Status asthmaticus ■ Pulmonary contusion ■ Smoke inhalation	■ Any pre-existing condition that is incompatible with recovery
	Veno-arterial	Refractory cardiogenic shock with potentially reversible heart conditions ■ Massive pulmonary embolism or haemorrhage ■ Bridging patients until transplant or insertion of a ventricular assist device ■ Salvage technique during cardiac arrest of unsuccessful but adequate cardiopulmonary resuscitation	

**The left ventricular assist device unloading allows myocardial recovery, facilitating device removal in the future without cardiac transplant. †A controversial use for patients who are unsuitable for cardiac transplant.*

How does it work?

Once in situ, the balloon is inflated to occlude most of the aorta during diastole and deflated in systole. This creates a counter-pulsation effect whereby the inflation of the balloon displaces blood both in an anterograde direction along the aorta towards the systemic circulation, and in a retrograde direction towards the coronary arteries, thereby increasing the coronary flow. In addition, as deflation occurs at the beginning of systole, it creates a vacuum effect in the aorta, decreasing the afterload of the left ventricle. The intra-aortic balloon pump therefore increases myocardial oxygen supply and decreases myocardial oxygen demand. The size of the impact is influenced by the size of the balloon, aortic compliance and the heart rate. At higher heart rates, the diastolic times are shorter, resulting in less filling time for the coronary arteries. The timing is coordinated by either an echocardiogram or systemic arterial pressure waveform monitoring, with inflation coinciding with the middle of the T-wave or the dicrotic notch, and deflation coinciding with the peak of the R-wave or just before the upstroke of the arterial waveform (Figure 1).

Table 2. Complications

Device	Complications	
General	■ Haemolysis ■ Thrombocytopaenia ■ Infection ■ Haemorrhage ■ Thrombosis	
Intra-aortic balloon pump	■ Rupture of the vessels or balloon itself ■ Cerebral or renal ischaemia as a result of malpositioning ■ Lower limb ischaemia as a result of occlusion of femoral artery ■ Balloon entrapment	
Ventricular assist devices	■ Cardiac tamponade ■ Fluid overload ■ Aortic regurgitation ■ Right heart failure (when left ventricular assist device is used alone)	
Extracorporeal membrane oxygenation	Suck down	■ Lower limb ischaemia as a result of occlusion of femoral artery
	Veno-arterial	■ Left ventricular distention and thrombus formation ■ Differential hypoxaemia and Harlequin syndrome
	Veno-venous	■ Blood recirculation between return and exit cannulae ■ Shunting*

**Blood bypasses the oxygenator if cardiac output is higher than extracorporeal membrane oxygenation flow.*

Weaning and management

Once the ventricular function improves and inotropic requirements are minimal, the intra-aortic balloon pump can be weaned over 6–12 hours by reducing the inflation:myocardial contraction ratio, and/or by reducing balloon sizes. It can never be stopped completely while in situ because of the risk of thrombus formation, but can be removed at the bedside with haemostasis achieved using manual pressure, followed by application of a pressure dressing.

Extracorporeal membrane oxygenation

What is the device?

This type of mechanical circulatory support was first pioneered in neonates, but is now being used with increasing frequency in adults. Extracorporeal membrane oxygenation

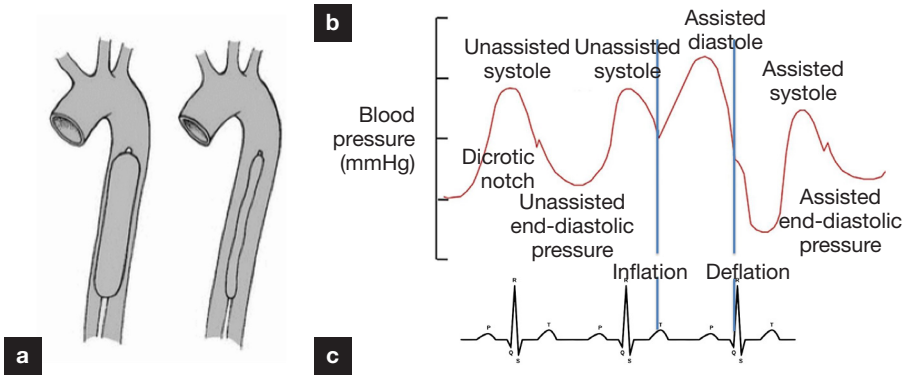

Figure 1. Intra-aortic balloon pump. a. The balloon is shown in its inflated and deflated positions. Its controlled inflation with helium, and subsequent deflation, can be coordinated with the arterial waveform (b) so that inflation should coincide with the dicrotic notch, and deflation just before the upstroke of systole. Alternatively, these timings can be coordinated with echocardiogram monitoring (c) with inflation coinciding with the middle of the T-wave, and deflation with the peak of the R-wave.

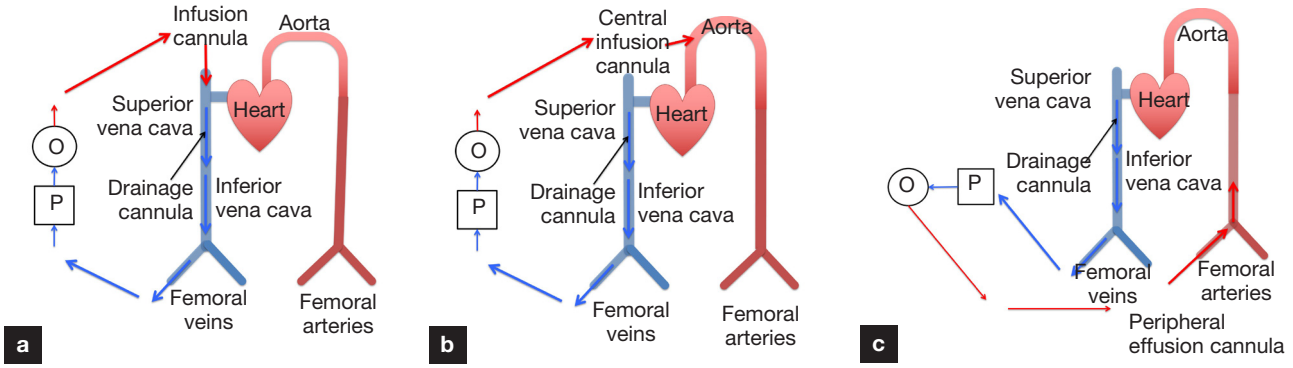

Figure 2. Extracorporeal membrane oxygenation. a. In veno-venous extracorporeal membrane oxygenation, a drainage cannula is normally inserted percutaneously into the inferior vena cava and blood is drawn up into the pump (P), through an oxygenator (O) (which performs gaseous exchange) with a heater/cooler attached to it, before being returned through the infusion cannula into the superior vena cava. This provides gas exchange support but no circulatory support, therefore requiring good heart function. b. In central veno-arterial extracorporeal membrane oxygenation, blood is again taken from the inferior vena cava, but after passing through the oxygenator it is returned into the ascending aorta, thereby providing both respiratory and circulatory support. c. In peripheral veno-arterial extracorporeal membrane oxygenation, instead of the blood being infused into the ascending aorta via a surgically placed cannula, it is infused into the femoral artery via a percutaneously inserted cannula.

consists of a large bore cannula in a vein connected to an airtight circuit with a centrifugal pump driving venous blood through a membrane oxygenator and reinfusing it at pressure into the systemic circulation via a vein or artery.

How does it work?

Extracorporeal membrane oxygenation is a quick and powerful short-term option to stabilise a patient. It allows recovery of organ function and then a decision of either weaning the device or upgrading to a longer-term strategy. Extracorporeal membrane oxygenation not only assists with the mechanical pumping of blood around the body, but also with oxygenation and decarboxylation of the blood, thereby 'resting' the heart and the lungs. There are two main types of extracorporeal membrane oxygenation: veno-venous extracorporeal membrane oxygenation and veno-arterial extracorporeal membrane oxygenation (Figure 2). In veno-venous extracorporeal membrane oxygenation, blood is removed from a cannula percutaneously inserted through the femoral vein into the inferior or superior vena cava, and returned via another cannula inserted through the internal jugular vein into the right atrium. The blood is therefore oxygenated before being circulated to the lungs, but the patient is still dependent on their own cardiac output.

Veno-venous extracorporeal membrane oxygenation is not traditionally considered a type of mechanical circulatory support. However, it may reverse haemodynamic instability in patients with refractory acute respiratory distress syndrome by alleviating right ventricular strain through positively impacting factors that lead to increased pulmonary vascular resistance such as hypercapnia and high airway pressures.

In veno-arterial extracorporeal membrane oxygenation, blood is removed from the venous circulation and returned into the arterial circulation via the oxygenator. This provides both gas exchange and haemodynamic support. It can be done either peripherally or centrally. Peripheral veno-arterial extracorporeal membrane oxygenation involves the removal of deoxygenated blood from the inferior vena cava, thereby bypassing the lungs and the heart, and oxygenated blood is returned to the femoral artery via a percutaneous cannula. To avoid ischaemia of the lower limb on the side of the cannula, an additional arterial cannula is inserted into the superficial femoral artery to perfuse the leg. While this option offers a less invasive approach, it can lead to a phenomenon called 'Harlequin syndrome' as discussed below. The more invasive central veno-arterial extracorporeal membrane oxygenation overcomes this issue through the surgical insertion of the arterial cannula into the ascending aorta.

Weaning and management

Once veno-venous extracorporeal membrane oxygenation is established, blood flow into the oxygenator is adjusted to keep oxygen saturations between 88% and 92% and the

partial pressure of oxygen at 8–10 kPa, while the sweep gas flow through the membrane oxygenator is adjusted to maintain a normal pH. Additionally, protective ventilation is continued, whereby mechanical ventilation of the lung with low tidal volumes is used in an attempt to reduce concurrent lung injuries. In veno-arterial extracorporeal membrane oxygenation, blood flow into the oxygenator is adjusted to achieve adequate mixed venous saturation and an acceptable perfusion pressure while avoiding a high left ventricular afterload. Meanwhile, the sweep gas flow is adjusted to achieve normocapnia.

Harlequin syndrome may occur when the patient has concomitant respiratory failure resulting in a hypoxaemic anterograde native cardiac output. This creates a mixing point, often in the aortic arch, where the cardiac output meets the retrograde extracorporeal membrane oxygenation blood flow. This can result in hypoxaemia in the coronaries and cerebral circulation. Additionally, the retrograde flow can cause increased left ventricular afterload leading to left ventricular distension, thrombus formation and loss of pulsatility, and thus may impair left ventricular recovery. Therefore, echocardiograms should be performed regularly to check for left ventricular distention, and/or a pulmonary artery catheter can be inserted to monitor pulmonary capillary wedge pressure (an indirect measure of left atrial pressure). A saturation probe and arterial line in the right arm can help monitor for Harlequin syndrome, and near-infrared spectroscopy can be used to monitor blood flow to the brain. The above issues may be remediated by the addition of an intra-aortic balloon pump and an Impella device and through optimum ventilatory management.

In both veno-arterial and veno-venous extracorporeal membrane oxygenation, it is important to monitor for the phenomenon of ‘suck down’ – a situation where the input to the pump is reduced either as a result of obstruction or vein collapse. Additionally, as with all types of mechanical circulatory support, coagulation management is vital as haemorrhage and thrombosis are common complications.

Patients can start to be weaned when, in the case of veno-venous extracorporeal membrane oxygenation, there are signs of lung improvement in the form of imaging, pulmonary compliance and arterial saturations. The gas flow through the oxygenator can be turned off while keeping the blood circulating but ceasing the support. Decannulation can be performed at the bedside by the intensive treatment unit team. In the case of veno-arterial extracorporeal membrane oxygenation, readiness to wean is determined by a thorough clinical and echocardiographic assessment according to suggested criteria (Ortuno et al, 2019) while decannulation is performed by vascular surgeons in theatre.

Ventricular assist devices

What is the device?

Ventricular assist devices provide a greater degree of cardiac support than the intra-aortic balloon pumps. Short- and medium–long-term (durable) ventricular assist devices exist, with the most widely used short-term device being the Impella (Abiomed, USA). This is inserted percutaneously through the femoral artery and delivers the tip of a pigtail catheter, housing an axial flow pump, across the aortic valve into the left ventricle. Blood is thus pumped from the left ventricle to an outlet in the catheter that sits on the aortic side of the valve.

In durable devices, an inflow cannula is inserted through the left (or rarely right) ventricular wall, and a centrifugal or axial pump draws blood up the inflow cannula and down an outflow graft inserted into the ascending aorta in left ventricular assist devices (or the pulmonary artery in right ventricular assist devices) (**Figure 3**). A driveline is tunnelled through the epigastrium, connecting the device to the console that houses the controls and also the battery. Currently, the incidence of driveline infections is a significant limitation although, in future, these devices are likely to have wireless charging systems.

How does it work?

Ventricular assist devices remove blood from the left or right ventricle and pump it into the systemic circulation (left ventricular assist device), pulmonary circulation (right ventricular assist device), or both (biventricular assist device). In doing this, ventricular assist devices reduce the workload of the heart, allowing the ventricles to rest while maintaining a cardiac output, and also limits deterioration in ventricular compliance from over-distention.

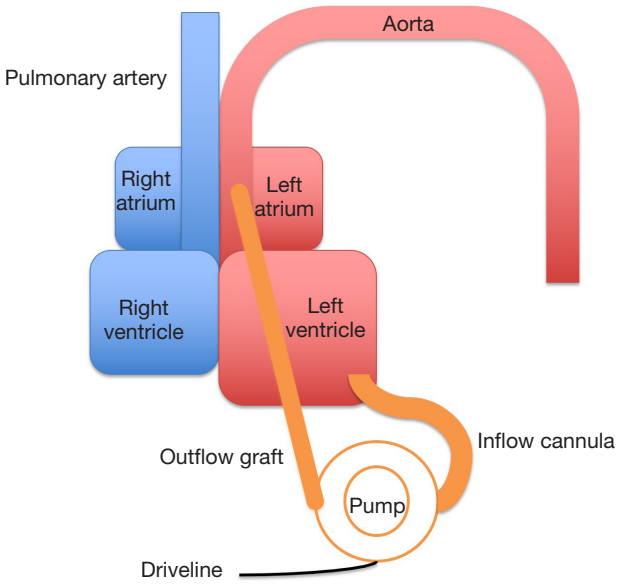

Figure 3. Ventricular assist device. An inflow cannula is inserted through the left ventricular wall. A centrifugal pump draws blood up the inflow cannula and down an outflow graft inserted into the ascending aorta. A driveline is tunnelled through the epigastrium connecting the device to the console that houses the controls and also the battery.

Ideally, left ventricular assist device support is used alone, but while right ventricular failure can improve after left ventricular assist device implantation, in over 20% of patients right ventricular function actually worsens as a result of mechanical interdependence and haemodynamic reasons (Harris and Kuppurao, 2012). In these circumstances, a biventricular assist device may be required.

The unique feature of ventricular assist devices compared to other mechanical circulatory support is that patients can be discharged home with a durable ventricular assist device in situ. This has had a dramatic impact on the management of certain groups of patients with end-stage heart failure. Patients with durable ventricular assist devices in situ could make for a surprising examination in an emergency department, as their pulse may be impalpable with continuous flow models, their blood pressure may be very difficult to assess with standard non-invasive blood pressure measurements, and they are able to tolerate otherwise lethal arrhythmias.

Weaning and management

Optimisation of international normalised ratio and antiplatelet therapy is key as patients are often over-coagulated (leading to cerebral haemorrhages), and can acquire coagulopathies from von Willebrand factor depletion by the device. Fluid balance and blood pressure must also be monitored strictly to prevent hypertension-related cerebral haemorrhages and hypotension-related suck-down events. Explantation is very rare in the UK, as most patients are awaiting transplantation. It is therefore crucial to regain as much of the patient's physical condition as possible while awaiting the major surgery. The timing of ventricular assist device explantation requires assessment of the residual ventricular function while using the lowest pump support allowed, taking care to avoid the risk of thrombus formation.

Conclusions

Mechanical circulatory support provides a means to assist cardiopulmonary physiology and offer vital support for critically ill patients. Three distinct devices exist, each with their own associated indications, contraindications and complications. As technology improves and understanding of optimum mechanical circulatory support deployment grows, their use in modern medicine will become more commonplace and thus they will be regularly encountered by medical professionals from all specialties.

Key points

- While use of mechanical circulatory support is increasing, its fundamental role and limitations remains poorly understood by many doctors.
- Mechanical circulatory support can be an effective treatment in selected pathologies, including myocardial ischaemia, pulmonary congestion, massive pulmonary embolic disease, postcardiotomy cardiogenic shock with failure to wean off bypass, right ventricular failure, bridge to heart and lung transplant and, increasingly, extracorporeal cardiopulmonary resuscitation.
- Intra-aortic balloon pumps increase coronary perfusion and reduce myocardial oxygen demand in a variety of cardiac conditions but current evidence does not show a benefit on mortality rates.
- Extracorporeal membrane oxygenation can provide both respiratory and circulatory support to patients.
- Ventricular assist devices can not only benefit patients with acute cardiogenic shock, but also provide support for ambulant patients in the community setting as a bridge to transplant and, in countries outside the UK, as a destination therapy.

Author details

[1]Department of Intensive Care Medicine, Barnet Hospital, Royal Free London NHS Foundation Trust, London, UK

[2]Department of Intensive Care Medicine, Royal Brompton & Harefield NHS Foundation Trust, London, UK

[3]Department of Intensive Care Medicine, The Royal London Hospital, Barts Health NHS Trust, London, UK

Conflicts of interest

The authors declare no conflicts of interest.

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Curriculum checklist

This article addresses the following requirements from the general internal medicine training curriculum

- Providing continuity of care to medical in-patients, including management of comorbidities and cognitive impairment
- Managing patients in an outpatient clinic, ambulatory or community setting, including management of long-term conditions
- Managing medical problems in patients in other specialties and special cases

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