THE EVOLUTION OF cardiovascular medicine has been dictated by the prevalence and high mortality of cardiovascular disease. The past 30 years have yielded an exponential increase in both knowledge and technologic progress in this field, from preventive cardiology and the movement toward gene therapy, to complex interventional therapeutics expanding the frontiers of minimally invasive procedures performed in the catheterization laboratory. These include high-risk percutaneous coronary interventions (PCIs) requiring temporary circulatory support and valvular interventions (percutaneous aortic valve replacement, mitral valvuloplasty).

The use and indications for PCI have expanded dramatically and continue to grow. PCI is currently the preferred method of revascularization, with more than 1 million procedures performed annually in the United States, more than twice the number of coronary artery bypass graft surgeries.

Along with this expansion, the complexity of patients and procedures performed continues to rise, requiring more involvement from different medical and surgical specialties, including a higher demand for anesthesiologists and critical care specialists. The development of percutaneous circulatory support for PCI and different forms of cardiogenic shock has led to more aggressive interventions in sicker patients who otherwise would not tolerate a cardiac surgical procedure and has opened a new era of possibilities, expanding the limits of traditional interventional cardiology and forcing exciting alliances with cardiovascular surgery and anesthesiology.

Over the past 3 decades, the incidence of cardiogenic shock has remained stable despite progress in the management of acute coronary syndromes. Despite innovative interventional therapeutics, the mortality of shock patients remains high (50%-70%). Irreversible pump failure remains the most important cause of death, and there is growing evidence of the role of systemic inflammation with resultant inappropriate vasodilation perpetuating the vicious circle and downward spiral of multifactorial circulatory failure.

Traditionally, the management of patients with acute cardiogenic shock has been limited to pharmacologic inotropic support. Technologic advances in mechanical circulatory support have also significantly improved the care of these patients. These devices range from intra-aortic balloon counterpulsation, left atrial-to-femoral arterial bypass, and transvalvular aortic percutaneous assist devices, to extracorporeal membrane oxygenation. The use of these devices is not limited to the emergency setting of acute coronary syndrome presenting with cardiogenic shock, but also in extending the envelope to elective complex cases in the catheterization laboratory for patients who otherwise would never survive a percutaneous coronary intervention or traditional open-chest cardiac surgical revascularization.

The development of the heart-lung machine was pivotal in the evolution of cardiac surgery as the direct predecessor of current technologies available for intraoperative cardiopulmonary bypass (CPB) and extracorporeal membrane oxygenation (ECMO). The concept of left-heart bypass for postoperative support in patients unable to be weaned from CPB was first described by Dennis et al in 1962. The expansion of the theory of aortic counterpulsation as an adjunct allowing for left ventricular systolic unloading and diastolic augmentation ultimately resulted in Kantrowitz et al’s 1968 report of clinical application of intra-aortic balloon pump (IABP) counterpulsation. More recently, the development of percutaneous extracorporeal circulatory support in the form of left atrial-femoral arterial bypass (TandemHeart; CardiacAssist Inc, Pittsburgh, PA) and transvalvular aortic axial flow devices (Impella Systems; Abiomed Inc, Danvers, MA) have revolutionized the care of patients in whom left ventricular unloading from IABP and inotropes alone are not sufficient to reverse or prevent cardiogenic shock. These patients usually have severe depression of cardiac function. Another high-risk group of patients is those with persistent ventricular tachyarrhythmias and ventricular dysfunction who require complex radiofrequency ablation procedures. These circulatory devices can be used temporarily as a bridge to procedure, a bridge to recovery, or a bridge to surgery.

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Percutaneous Left Ventricular Assist Devices: Clinical Uses, Future Applications, and Anesthetic Considerations
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The use of these devices is increasing, and the usual location is the catheterization laboratory, a typically unfamiliar place for the anesthesiologist. The purpose of this review is to describe the different extracorporeal circulatory assist devices, clinical uses, future applications, and anesthetic implications of this growing technology.

**Rationale for Percutaneous Assist Devices**

The therapeutic goal of percutaneous extracorporeal circulatory support or left ventricular assist devices is to restore or maintain normal hemodynamics and organ perfusion in cardiogenic shock with severe myocardial failure or to serve as support for a procedure in complex high-risk percutaneous interventions. Although there are different devices with a variety of mechanisms of left ventricular assistance, all of them have theoretic beneficial effects of acute left ventricular unloading including reducing ventricular strain and improving remodeling of the acute failing heart. In addition, peripheral organ and skeletal muscle perfusion can be maintained. Although this hypothesis has not been tested in randomized controlled studies, there are some experimental data showing a reduction of infarct size and improved microcirculatory perfusion in dogs supported by a left ventricular assist device compared with control animals supported by IABP alone.3,10

The recovery of myocardial function after successful revascularization following acute myocardial infarction usually requires several days. Generally, intra-aortic balloon counterpulsation is the method of choice for mechanical assistance and hemodynamic stabilization of these patients; however, the lack of active cardiac support and the need for accurate synchronization with the cardiac cycle are the main limitations of this common device. In some patients with profound persistent myocardial dysfunction or persistent tachyarrhythmias, the support provided by this method is insufficient to reverse circulatory failure and shock. Accordingly, the use of percutaneous left ventricular assist devices (pLVAD) with active circulatory support could be beneficial in this setting as a bridge to recovery. Moreover, in patients who suffer mechanical complications after myocardial infarction or those who do not recover, pLVADs can be used as a bridge to surgery for the implantation of a long-term left ventricular assist device as destination therapy or a bridge to transplantation. These devices are designed for short-term support with a maximum use of 14 days.12

Another important use for pLVADs is as a bridge to procedure. This is seen commonly in the catheterization laboratory with elective complex PCI in patients with high-risk coronary disease with or without baseline left ventricular dysfunction.

**The TandemHeart Percutaneous Transseptal Left Ventricular Assist Device**

The TandemHeart (Cardiac Assist Technologies, Inc, Pittsburgh, PA) is a percutaneous transseptal left atrial-to-femoral arterial extracorporeal circulatory device that provides left-heart bypass designed for short-term circulatory support. The concept of left-heart bypass is not new and was initially designed for postcardiotomy shock in patients unable to be weaned from CPB.13 This technique was first described by Dennis et al in 1962 with venous access achieved from the jugular approach. This system was initially limited and lacked widespread use because of the unavailability of an adequate transseptal cannula for full circulatory support and a high rate of hemolysis and thrombus formation with the high-speed centrifugal pumps used. It was not until the 1990s when the transfemoral percutaneous approach of this type of circulatory support for patients undergoing high-risk coronary interventions was described for short-term use.14

The TandemHeart is a new generation of low-speed centrifugal continuous-flow pump that has been approved for short-term (6 hours) circulatory support by the Food and Drug Administration, although it has been used for days for hemodynamic support. These characteristics result in a theoretic reduction of hemolysis and thrombus formation. The system is capable of delivering up to 4 L/min of flow at 7,500 rpm (up to 5 L/min if an extended-flow cannula set is used). This circulatory assistance is possible regardless of the patient’s rhythm. In a prospective randomized trial comparing IABP and TandemHeart pLVADs in patients with revascularized myocardial infarction complicated with cardiogenic shock, the group supported with pLVADs had more significant improvement of hemodynamics and metabolic variables compared with IABP; however, mortality was similar, and there were more complications associated with pLVADs. These results were replicated in another small randomized trial. The TandemHeart has been used successfully as a bridge to procedure in patients with severe left ventricular dysfunction undergoing complex coronary interventions. The most important limitation of the left atrial-to-femoral arterial bypass is the requirement of large arterial and venous cannulae to achieve adequate circulatory support and the need for transseptal puncture and dilation. However, no significant residual left-to-right shunt has been observed after this procedure.16

**Physiology and Hemodynamic Effects**

In comparison to the left ventricular unloading provided by the IABP, the TandemHeart pLVAD actively augments cardiac output and has the capability of completely replacing left ventricular function, achieving flows up to 5 L/min. The device functions as a left-heart bypass with in-parallel circulatory support that drains fully oxygenated blood from the left atrium (provided there is normal lung function) to pump it retrogradely via the femoral artery, reducing cardiac work load, oxygen demand, and left ventricular filling pressure. Animal studies have shown a significant decrease in infarct size by the use of this type of device.19

**Indications**

The TandemHeart pLVAD may be used as temporary support for patients with cardiogenic shock or to support patients during critical complex PCI, particularly in the presence of severe LV dysfunction. In general, these patients are poor surgical candidates because of severe comorbidities or inaccessible disease as are patients in whom the IABP support alone will not suffice to maintain physiologic hemostasis (Table 1).
Device Description and Insertion

The TandemHeart is usually inserted in the catheterization laboratory and requires a traditional transseptal puncture with the Brockenbrough needle into the left atrium via femoral vein access. The inflow transseptal cannula is a 21F polyurethane catheter with a large end hole and 14 side holes to facilitate left atrium decompression. The centrifugal flow pump is a low-prime volume device (10 mL) that includes a 6-blade rotating impeller that is powered by a direct current microprocessor-controlled electromagnetic rotary motor. The system includes 2 controllers, a primary and a backup, which are constantly ready for use and have extensive self-diagnostics with alarm features to ensure continuous support. Built-in batteries allow uninterrupted circulatory assistance for 1 hour to facilitate transport or in case of outage. Furthermore, a pressure transducer is used to monitor the infusion pressure and alerts to potential blockages in the infusion catheter. The outflow cannula is 15F to 17F and is inserted in the common femoral artery (Fig 1). Because the outflow cannula does not reach the abdominal aorta, it does not preclude the concomitant use of IABP.

After percutaneous puncture of the femoral vein and standard transseptal puncture and predilation of the fossa ovalis, the venous inflow cannula is inserted in the left atrium, and position is confirmed with contrast injection. Right-to-left shunting can potentially occur if not all the side holes of the transseptal cannula are located in the left atrium and can be suspected with sudden oxygen desaturation of the arterial blood. Subsequently, the arterial inflow cannula is inserted in the ipsilateral or contralateral common femoral artery using the Seldinger technique and advanced until the tip is in the common iliac artery. After adequate air removal, the cannulae are connected to the centrifugal pump by standard heparin-coated Tygon tubing (US Plastic Corp, Lima, OH). Oxygenated blood is retrieved from the left atrium and pumped into the abdominal aorta via the femoral inflow cannula. Typical flows achieved are about 3.5 L/min with the 15F arterial outflow cannula and 5.0 L/min with the 17F. The entire assembly and institution of mechanical circulatory support can be achieved within 30 minutes in the hands of experienced operators, and usage up to 14 days has been reported.18,20

Maintenance and Explantation

Adequate systemic anticoagulation with intravenous heparin is necessary to reduce the risk of thromboembolic complications. After successful weaning of circulatory support because of myocardial recovery or after a critical revascularization procedure, the device can be explanted easily percutaneously. After the discontinuation of heparin, the arterial cannula is removed, and manual compression or suture closure of the puncture site is performed until adequate hemostasis is achieved. After explantation of the venous transseptal cannula, there is a small residual atrial septal defect that usually closes within 4 to 6 weeks.18

Contraindications

The TandemHeart used as a pLVAD depends on adequate right ventricular function for optimal circulatory assistance. Therefore, the presence of right ventricular failure or predominantly right acute myocardial infarction is a relative contraindication.

Table 1. Indications for pLVADs

<table>
<thead>
<tr>
<th>Indication</th>
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<tbody>
<tr>
<td>Cardiogenic shock</td>
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<tr>
<td>Postmyocardial infarction</td>
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<tr>
<td>Postcardiac surgery</td>
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<tr>
<td>Chronic heart failure with acute hemodynamic decompensation</td>
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<td>Acute myocarditis</td>
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<td>Myocardial contusion</td>
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<td>Refractory ventricular arrhythmias</td>
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<td>High-risk percutaneous cardiac procedures</td>
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<tr>
<td>Complex PCI (left main disease and multivessel PCI)</td>
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<tr>
<td>Pre-existing severe left ventricular dysfunction</td>
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<td>Acute ongoing myocardial ischemia</td>
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<td>Complex radiofrequency ablation procedures for ventricular arrhythmias</td>
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<td>Preoperative stabilization for cardiac surgery</td>
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<tr>
<td>Active myocardial ischemia</td>
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<tr>
<td>Acute mechanical complications of myocardial infarction (acute ischemic mitral regurgitation and VSD)</td>
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<td>Severe preoperative left ventricular dysfunction</td>
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<td>Bridge to recovery</td>
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<tr>
<td>Postmyocardial infarction</td>
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<tr>
<td>Postcardiac surgery myocardial stunning</td>
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<td>Bridge to permanent therapy</td>
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<tr>
<td>Surgically implanted long-term LVAD</td>
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<td>Heart transplant</td>
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Abbreviations: VSD, ventricular septal defect; LVAD, left ventricular assist device; IABP, intra-aortic balloon pump; ECMO, extracorporeal membrane oxygenation.

Fig 1. The TandemHeart. (A) A graphic of the percutaneously inserted device in place. Note the femoral venous transseptal and arterial cannula connected to the TandemHeart centrifugal pump. (B) A close-up view of the centrifugal pump. (C) A close-up view of the TandemHeart Transseptal Cannula. (Courtesy of CardiacAssist, Inc.) (Color version of figure is available online.)
dication for the classic use of this device as designed for left ventricular support. However, the system can be configured as a right ventricular assist device with pulmonary arterial and right atrial cannulation, or 2 systems can theoretically be used in combination for biventricular support. The presence of a ventricular septal defect poses the risk of right-to-left shunting and subsequent hypoxemia, and, similarly to the IABP, severe aortic insufficiency may cause left ventricular overdistention and subendocardial ischemia. The presence of severe peripheral arterial disease and femoral grafts may preclude the use of this device as well as any contraindication for systemic anticoagulation. Moreover, the use of a large venous transseptal cannula is a relative contraindication in patients with an inferior vena cava filter. Nevertheless, the successful use of this device has been described in this setting, without inferior vena cava filter displacement.

Complications and Limitations

The use of large-bore cannulae and transseptal puncture is not devoid of risk. General complications related to the femoral vessel cannulation include bleeding, infection, and limb ischemia. Unique complications of this device include paradoxical embolism caused by the transseptal atrial cannulation, accidental coronary sinus, or posterior right atrial wall puncture with cardiac tamponade. Cannula dislodgement can be catastrophic in the setting of profound shock or during a critical portion of a complex PCI. The presence of a ventricular septal defect can happen during cardiopulmonary resuscitation, and reposi- tion with fluoroscopic guidance or echocardiogram should be obtained immediately if suspected.

Although the beneficial physiologic effects of this device have been shown, there have been limited studies in humans to date, and none has had the appropriate power to prove a substantial mortality benefit. Another potential limitation is the added theoretic propagation of inflammatory response associated with extracorporeal bypass circuits.

Anesthetic Implications

Considering the complexity of patients and procedure, the majority of these cases are performed under general anesthesia despite the fact that the patient’s physiologic status will be supported during the intervention. However, there is anecdotal experience of the performance of complex procedures with this device under monitored anesthesia care.

The rate of complications and the ease of cannula placement depend on the institution and expertise of the interventional cardiologist and team. Initial trials should be performed under general anesthesia, with adequate preparation for emergent surgical support because of complications during transseptal placement or cannulation. Blood should be ready in the room, and a surgical scrub team should be notified for possible emergent transfer to the operating room. Appropriate venous access includes peripheral as well as central vessels. Monitors should include direct radial arterial pressure monitoring, central venous, and pulmonary artery catheter. Initially, cardiac output is high with the circulatory support (7–8 L/min) but usually drops during critical procedures because the left ventricle may stop contracting. In severely compromised patients, the use of a transesophageal echocardiography, continuous cardiac output pulmonary artery catheter, or mixed venous oxygen monitor can help tailor the hemodynamic support before, during, and after circulatory support by the pLVAD.

The induction of anesthesia should proceed similarly to the severely compromised cardiac surgical patient, understanding the negative inotropic and vasodilatory effect of most intravenous induction agents. Not uncommonly, the radial artery is cannulated before the induction for continuous arterial blood pressure measurements for a more controlled induction of anesthesia.

Before insertion of the cannulae, the patient needs to be anticoagulated with a goal of an activated coagulation time (ACT) >300 seconds. Heparin is usually the anticoagulant of choice; however, there are protocols using direct thrombin inhibitors, like bivalirudin, to be used in cases of contraindica-
tion to heparin therapy (heparin-induced thrombocytopenia).

High vigilance for complications during cannulae placement is vital for an effective and timely response. Complications including hypoxemia caused by right-to-left shunt, hypoten-
sion, cardiac tamponade, and bleeding can be catastrophic.

Before starting the centrifugal pump and adequate deairing, a fluid bolus load of 1 L of isotonic crystalloid solution or 500 mL of colloid is administered to fill the heart at the time of pump start. Vigilance for air emboli is critical because a new atrial septal defect is created, and all intravenous catheters should be inspected for air to avoid this complication. Some advocate the use of intravenous air filters to avoid this complication.

Inotropic support should be in line and available. During emergence, a multidisciplinary approach led by the interventional cardiologist will wean the patient from the partial bypass by reducing the revolutions per minute and assisted flow to achieve an approximate mean arterial blood pressure of 70 to 75 mmHg. At the end of the procedure, the cardiologist removes the cannulae and repairs the vessels, usually with a vascular closure device after the reversal of anticoagulation with protamine (if heparin is used).

The decision to extubate the patient depends on the length of the procedure and the patient’s condition before and after the intervention. It is not uncommon to require postprocedure mechanical ventilation in the coronary care unit.

In patients with atrioventricular conduction abnormalities, consideration should be given to placing ventricular pacing wires in cases of complete heart block or asystole before circulatory support. If wires are present at the time of cannula insertion, they should be withdrawn before transseptal cannula- tion or the cardiologist should be notified. In experienced institutions with extensive expertise, the TandemHeart can be readily placed with minimal complications; in these cases, consideration to perform the procedure under sedation can be made. However, constant vigilance by the anesthesiology personnel still is warranted as is hemodynamic monitoring.

THE IMPELLA CIRCULATORY SUPPORT SYSTEM

The Impella system (Abiomed, Danvers, MA) is another type of pLVAD that has a different mechanism of ventricular unloading and circulatory assist. It consists of a miniature axial
flow rotary blood pump that is positioned across the aortic valve. The system actively unloads the ventricle by drawing blood through the distal port within the ventricular cavity and pumping it into the ascending aorta through the proximal port of the device. The inflow cannula pump is inserted via the femoral artery and advanced past the aortic valve under fluoroscopic guidance (Fig 2). This device is designed to provide short-term ventricular support for several hours to days and comes in 2 different sizes: the Impella system LP 2.5 and 5.0 with a 12F and 21F pump diameter, respectively, and capable of providing 2.5- and 5.0-L/min flows. Both systems are mounted on a 9F pigtail catheter.27 There are percutaneous and surgically implantable versions (LP and LD) as well as a surgical implantable Impella for right ventricular support (RD). Although the femoral artery is the most common access, a right axillary approach has been used intraoperatively for postcardiotomy shock in patients with severe peripheral arterial disease.28

The concept of axial flow pumps across the aortic valve for circulatory assist was first described by Wampler et al29 in 1988; however, despite initial optimism, the success of the Hemopump (Medtronic, Inc, Minneapolis, MN) was hampered by a high rate of complications and technical difficulties.12,30 A resurgence of this concept with improved technology led to the development of the newer axial flow systems described previously. The Impella system has already received CE certification for use in the European Union as well as Food and Drug Administration approval in the United States (2006) for 5 days’ use. Although there are some case reports with successful bridge to recovery,11 the most common use of this device to date is for complex patients undergoing high-risk PCI.32 A recent randomized controlled trial comparing its use against the IABP for the treatment of cardiogenic shock caused by myocardial infarction showed superior hemodynamic support with the Impella LP 2.5.33 However, a recent meta-analysis of controlled trials comparing pLVADs with IABPs failed to show a 30-day mortality benefit.34

Physiology and Hemodynamic Effects

The transvalvular axial flow pumps provide nonpulsatile circulatory support and left ventricular unloading with increased cardiac output, decreased myocardial workload, wall stress, and oxygen consumption without the need for concomitant venous access and transseptal puncture. This is the main difference with the TandemHeart. The Impella system provides in-series circulatory support (left ventricular to aortic) instead of in-parallel assistance (left atrial to aortic).

Indications

Similar to the TandemHeart, the indications for the Impella include the need for partial circulatory support in patients with cardiogenic shock as a bridge to recovery or a bridge to procedure in complex high-risk PCI (Table 1).

Implantation and Device Description

The Impella Recover system LP 2.5 model is suited for percutaneous implantation, whereas the LP 5.0 model requires surgical cutdown of the femoral artery for insertion. When the percutaneous system is used, a 13F or 14F sheath is placed into the femoral artery using the Seldinger technique. Subsequently, a 5F pigtail catheter is used to access the ventricle in a retrograde fashion. This catheter is then exchanged over a wire for the 12F catheter pump assembly, and, once position is confirmed in the left ventricular cavity, circulatory support is initiated and titrated using the 9 different performance levels (P1-9, maximal flow of 2.5 L/min). Proper placement should be confirmed before initiation.

The Impella 2.5 system consists of the following components: (1) an Impella 2.5 catheter with built-in pump, (2) an Impella console with portable battery, (3) a power supply and cable, and (4) a Braun Vista basic infusion pump (B. Braun Medical Inc, Bethlehem, PA).

Maintenance and Explantation

As with other pLVADs, systemic anticoagulation with intravenous heparin is necessary to reduce the risk of thromboembolic complications. The ACT is used to monitor this during the procedure. After an ACT of 250 to 500 seconds is achieved, the device is inserted as described previously. The ACT should be maintained at 160 to 180 seconds after device insertion and throughout circulatory support. A unique feature of this device is the need for a purge system that delivers rinsing fluid to the Impella pump. This is
achieved with the Braun Vista pump, which uses 20% dextrose plus heparin, 50 IU/mL, solution.

Two weaning protocols have been described by the manufacturer; however, physician discretion and institutional-driven protocols may be used. The rapid weaning protocol consists of decreasing the performance level in 2-level steps every several minutes until P2 level is reached. The circulatory support should be maintained at this level for at least 10 minutes before discontinuing the device. After this interval, if the patient remains stable, the performance level is decreased to P1, the catheter is pulled back into the aortic root, and the pump is stopped. Subsequently, the catheter pump is explanted, and a percutaneous arterial closer is usually needed.

When supporting sicker patients with cardiogenic shock, the slow weaning protocol may be more appropriate. This is achieved by decreasing the pump performance level 2 levels every 2 to 3 hours. Caution is needed to not decrease the pump performance level below P2 while the catheter is in the ventricle because retrograde flow may occur. Once the patient is stable on performance level P2 for at least 2 hours, the performance level is reduced to P1 and the catheter is pulled back to the aorta to subsequently stop the pump. After the discontinuation of heparin and an ACT <150 seconds, the cannula is removed as described previously.

Contraindications

Because of the transvalvular nature of this device, it is contraindicated in the presence of an aortic valve prosthesis, a severely calcified aortic valve with or without aortic stenosis, significant aortic regurgitation (grade 2 or more), and severe peripheral arterial disease. Other relative contraindications include abdominal or thoracoabdominal aortic aneurysms, aortic dissection, and the presence of femoral-popliteal bypass grafts. The use in the presence of aortobifemoral grafts has never been described and a vascular surgeon should be consulted if used for elective circulatory support; as an alternative approach, the axillary or subclavian artery should be considered in this patient population.

Complications and Limitations

Potential complications of Impella pLVAD use include cerebral vascular accident, aortic valve injury with resultant aortic insufficiency, arrhythmia (atrial and ventricular), cardiac tamponade, infection, vascular injury, limb ischemia, bleeding, and coagulopathy. This device, like all centrifugal pumps, can provoke hemolysis and thrombocytopenia. Although the use of the Impella has gained significant popularity for temporary circulatory support for cardiogenic shock and high-risk PCI, because of the obviation of concomitant venous cannulation and transseptal puncture, the hemodynamic response to the device is variable and occasionally can cause left ventricular volume overload. This phenomenon could be related to malpositioning of the pump (too deep) or peridevice leak, limiting proper coaptation of the aortic valve leaflets. Echocardiography to monitor left ventricular size and function is useful. Another limitation is the flow capabilities of the percutaneous Impella LP 2.5 (up to 2.5 L/min) compared with the TandemHeart (up to 5 L/min). This, however, would not be a factor with the use of the larger Impella LP 5.0 (up to 5 L/min), which is not currently approved for use and requires surgical insertion.

Anesthetic Implications

Although potentially less invasive than the TandemHeart, the complexity of patients mandates the presence of anesthesia personnel. The initial experiences with the Impella placement should be performed under the controlled environment of general anesthesia. Once there is comfort with the placement, these cases are usually performed under monitored anesthesia care.

Anecdotal experience with monitored anesthesia care with much less invasive monitoring has been successful in the authors’ institution. The use of standard American Society of Anesthesiologists monitors is usually sufficient because direct arterial blood pressure can be obtained with the device. Adequate peripheral venous access should be obtained before the procedure. No central venous access is usually required. Understanding the potential complications of the device is important for prompt action and troubleshooting.

The use of this device in patients with cardiogenic shock usually is in the presence of concomitant respiratory failure with a need for mechanical ventilation. Adequate central venous access including a pulmonary artery catheter may be required to guide inotropic and vasopressor support, most importantly during weaning from circulatory support.

EXTRACORPOREAL MEMBRANE OXYGENATION IN THE NONOPERATIVE SETTING

A limitation of percutaneous left ventricular circulatory support is the dependence on the lungs for oxygenation and ventilation. Extracorporeal membrane oxygenation (ECMO) consists of a blood pump and a circuit with a built-in oxygenator providing full cardiopulmonary support. The term extracorporeal life support (ECLS) has been coined for the use of ECMO as a temporary support in cardiopulmonary collapse refractory to cardiopulmonary resuscitation under medical direction. Usually, venous-arterial bypass is achieved; however, in cases of respiratory failure alone, venous-venous ECMO can be used, even in the trauma setting.

The incorporation of ECLS in the standard resuscitation algorithms is unrealistic because of the lack of widespread availability. However, the use of ECMO in tertiary care centers with adequate capabilities for the rapid institution of ECLS in the appropriate clinical setting has invaluable potential. Recently, guidelines for indications for ECLS were published by the French Ministry of Health to aid in the critical rapid decision-making process and limit the futile use of this technology. In adults, a 16F to 18F arterial cannula is inserted via a femoral artery into the descending aorta and an 18F to 20F venous cannula inserted via the femoral vein into the right atrium. After appropriate deairing, these cannulae are connected to the external pump and membrane oxygenator. The pump is primed with a crystalloid-colloid solution (depending on the institution), and, once this is achieved, blood is withdrawn from the right atrium, pumped through a heat exchanger and membrane oxygenator, and returned via the femoral artery to the aorta. The circulatory support is retrograde continuous.
flow, but usually pulsatile arterial pressure is maintained unless ECMO is providing complete cardiopulmonary support. Limitations of ECMO in the nonoperative setting include a lack of direct LV unloading, increased LV afterload, and the requirement of more personnel (ECMO specialists and perfusionists); furthermore, it produces a more pronounced systemic inflammatory response. It requires the same level of anticoagulation as the previously described devices, and concomitant IABP counterpulsation can be used, especially in the context of myocardial ischemia. In the era of partial circulatory support, the role of ECMO in the nonoperative setting is limited to refractory cardiopulmonary failure in which circulatory assistance by pLVAD is not sufficient because of concomitant respiratory failure. Moreover, this technology can be used to support homeostasis as a bridge to emergent cardiac surgery.

**FUTURE APPLICATIONS AND DEVICES**

The indications for temporary mechanical circulatory assistance are increasing, and the role of this technology in current practice is growing with more complex patients and aggressive percutaneous interventions. As the technology improves, the current devices get smaller and achieve better performance. New devices on the horizon include the LIFEBRIDGE system (Medizintechnik GmbH, Ampfing, Germany), which is a portable, modular, rapidly available mechanical circulatory support that could be used for short-term peripheral CPB for acute cardiopulmonary failure or as a bridge to procedure for high-risk PCI (Fig 3). The system has achieved CE certification, and the clinical introduction of the system has started in Europe. Although the LIFEBRIDGE is not approved by the Food and Drug Administration, there are numerous theoretic and practical advantages over other systems discussed previously. It is simple to use, safe, and practically a “plug-and-play” device. The size, weight, and semiautomatic priming and deairing functions make it ideal for the emergency setting and for use in the catheterization laboratory or any emergency setting outside the operating room. Furthermore, the state-of-the-art safety features, such as active intra-aortic air emboli detection and management and flow and level monitoring, make this device unique. The device is capable of providing full cardiopulmonary support with flows up to 6 L/min (4.1 L/min if peripheral cannulation) and adequate gas exchange. The unique characteristics of this device would make it ideal for full cardiopulmonary support in the catheterization laboratory, for transport, and even as an alternative to the standard CPB machine used for cardiac surgery. Anesthesiologists will be seeing more of this technology, stretching the limits of minimally invasive procedures and support.

**CONCLUSION**

The management of cardiogenic shock has evolved with the introduction of percutaneous mechanical circulatory support. The currently available temporary ventricular assist devices differ in the mode of assistance and complexity. Similarly, these devices will revolutionize the field of interventional cardiology, expanding the frontiers of minimally invasive procedures performed in the catheterization laboratory. As these devices get approval for clinical use, higher complexity of patient care will be expected in these remote locations for the anesthesiologist. It is of vital importance to be up to date in the technologic advances in this field and to actively participate in the periprocedural management of these patients. These devices not only will be used for a bridge to recovery in patients with cardiogenic shock, but also as a bridge to high-risk PCI or a bridge to surgery, and also may become an integral part of cardiopulmonary resuscitation in tertiary care centers (ECLS). It is important to note, however, that although this promising technology has been shown to improve hemodynamic parameters compared with the IABP alone, further studies will be needed to solidify their use and show long-term clinical outcome benefits.
PERCUTANEOUS LEFT VENTRICULAR ASSIST DEVICES

REFERENCES


36. Thomopoulou S, Manginas A, Cokkinos DV: Initial experience with the Impella Recover LP 2.5 micro-axial pump in patients under-


