Cardiac mechanical assist devices are used during periods of hemodynamic instability and persistent low cardiac output in an attempt to restore normal hemodynamic parameters. The primary goal of their use is to normalize inotrope and drainage of vital organs so that kidney and liver function return to normal with improved hemodynamic potential. The deleterious effects of elevated atrial pressure on many of the major organs are well known, with the lungs being most adversely affected. Increased central venous pressure is also particularly detrimental to the liver and kidneys, causing outflow disorders that compromise organ function. Elevated atrial and central venous pressures, secondary to ventricular dysfunction, are often rapidly normalized by the use of cardiac mechanical assist devices.

There is a stepwise progression of therapy that is followed in the intensive care unit with respect to cardiac assist interventions. Therapy begins with inotropic and vasodilator drugs and, if the sought-after end point is not achieved, typically progresses to the use of an intra-aortic balloon pump. Ultimately, mechanical ventricular assist device placement may be necessary. In this chapter, we will briefly discuss these devices with special emphasis on the indications, contraindications, placement, complications, and potential pitfalls.

**INTRA-AORTIC BALLOON PUMP**

**Indications**

- Acute myocardial infarction and shock: 10% to 15% of acute myocardial infarctions may require hemodynamic support with the temporary use of an intra-aortic balloon pump (Fig. 122.1). This may translate into as many as 1.5 million patients annually.
- Unstable angina
Section XII: Cardiovascular Disease and Dysfunction

Figure 122.1. Intra-aortic balloon pulsation (IABP). Example of standard 7.5 French 40-mL IABP.

- Prophylaxis for high-risk surgery or percutaneous coronary intervention
- Acute mitral insufficiency
- Ventricular septal rupture following an ischemic event (usually several days after ischemic insult)
- Postcardiotomy failure: Inability to separate patient from cardiopulmonary bypass following cardiac surgical procedure
- Traumatic myocardial contusion with low cardiac output

Contraindications

- Aortic insufficiency: Leaking of the aortic valve makes the use of an intra-aortic balloon pump potentially detrimental. During periods of diastolic augmentation, enhanced reversal of flow actually exacerbates the aortic insufficiency.
- Atheromatous aorta: Patients who are known to have severe atheromatous disease of the aorta are poor candidates for balloon pump therapy. There is the risk of atheroembolization, either distally or retrograde into the cerebral vasculature, during pump use or manipulation.
- Severe peripheral vascular disease or aortic dissection: The balloon pump is typically inserted in a retrograde fashion from the groin. This relative contraindication of peripheral vascular disease can be overcome by the use of alternate insertion techniques.

Techniques of Insertion

The most commonly used method of intra-aortic balloon pump insertion is via the retrograde approach from percutaneous access to the femoral artery (Fig. 122.2). This can be performed with or without a vascular sheath. Typically the femoral artery is accessed with a needle. A wire is then passed retrograde into the descending aorta. A sheath may or may not be placed depending on the size of the femoral artery and the circumstances. The balloon pump is then carefully inserted over the wire into the descending aorta to a point immediately distal to the left subclavian artery. When there has already been an incision made to the groin related to coronary artery bypass cannulation or some other intervention, it is possible to insert the balloon pump via direct arterial access.

In special circumstances, there are alternate sites for insertion. This is especially true in patients who either have their balloon pump for an extended period of time or have a need for ambulation during balloon pump use. In these circumstances,
a balloon pump may also be placed directly through the axillary artery (1). When placed via the axillary artery, a sheath is not routinely used for placement. In more extreme circumstances, placement may require an antegrade approach either directly into the arch or through a small graft sewn onto the ascending aorta or arch and tunneled to the chest wall (2,3). This method may be necessary for patients with coexisting peripheral vascular disease and postcardiotomy failure to wean during cardiopulmonary bypass.

**Verification of Location**

It is important that the appropriate location of the balloon pump be confirmed after insertion. It should be positioned just distal to the left subclavian artery in the descending thoracic aorta (Fig. 122.3). A more proximal placement risks an increased incidence of cerebral atheroembolization or of thromboembolization from microthrombi forming on the balloon pump itself. A more distal placement may cause the pump to impede the visceral arteries. The location of the balloon pump may be verified either by fluoroscopy or a chest roentgenogram. The tip should be high in the left chest in appropriate relation to the aortic arch. Another convenient mechanism to verify location involves using transesophageal echocardiography if performed concurrently with balloon pump insertion.

It is also important to select the appropriate sized balloon pump for the patient. Balloon pumps are manufactured in various sizes, ranging from those appropriate for a small infant to those used in large adults (Fig. 122.4). The standard adult size is 40 mL. The manufacturer's labeling and recommendations and the patient's habitus should be considered in size selection.

**Mechanism of Action**

There are two complimentary effects of an intra-aortic balloon pump. The first is the diastolic augmentation of coronary blood flow. The balloon pump is carefully timed to the cardiac cycle so that the pump inflates during aortic valve closure and thus enhances the diastolic pressure in the proximal aorta. This allows increased coronary blood flow and enhanced myocardial oxygen delivery. The second action involves the afterload reduction at the time of cardiac systole, thereby allowing enhanced runoff for the failing ventricle. The balloon should be properly timed to deflate during aortic valve opening, thereby creating a pocket of reduced afterload and thus enhancing the ability of the heart to eject the blood during systole. This action serves to lower the left ventricular end systolic volume. Both of these mechanisms augment left ventricular function and serve in complementary fashion to help those patients with right ventricular dysfunction. It is a common misperception that a balloon pump is not beneficial, or indicated, for patients with right ventricular dysfunction. Additional benefit is derived from the reduced left ventricular end-diastolic pressure and left atrial pressure, thereby allowing increased forward flow and decreased afterload for the failing right ventricle.

**Complications**

Although complications related to balloon pump insertion and use are relatively infrequent, they can be quite serious. The first potential complication can occur during insertion of the balloon pump and involves direct trauma to the arterial insertion site. It is important that insertion occurs relatively high in the thigh in the femoral artery, near the inferior edge of the inguinal ligament. It is possible for a misplaced balloon to shear off one of the major arterial branches. Misplacing the balloon through
a smaller-caliber artery may completely occlude the artery and create an ischemic limb. In arteries that are not particularly calcified, it is relatively easy to use the dilator and place the balloon pump without the use of a vascular sheath. This serves to reduce the maximal diameter of obstruction in the artery, and perhaps reduces the potential for thrombus within the artery. There is also the potential for mishap in both placement and location of intra-aortic balloon pumps. It is important to remember that when the balloon pump is placed as part of a cardiopulmonary bypass procedure, the blood is equally oxygenated in the arterial and venous vessels because of the bypass oxygenator. Additionally, there is zero pulsatile flow at the time of insertion, making it difficult to differentiate artery from vein. This situation has led some to inadvertently placed balloon pumps via the femoral vein into the right atrium. Additionally, hemodynamic instability at the time of insertion may also lead to suboptimal confirmation of balloon pump location. Improper placement can thus lead to impingement of the arch vessels, causing cerebral ischemia or thromboembolism.

In more chronic management of the balloon pump, ranging from several days to weeks or months, infectious complications become more predominant. In addition to meticulous sterile insertion techniques, balloon pumps also require daily attention from the nursing staff. Like any other percutaneously inserted central catheter, they have the potential to become a source of infection. Attention to the insertion site for signs of erythema or purulence and close monitoring of the patient’s temperature is mandatory in all patients using a balloon pump. When a patient’s hemodynamic status fails to stabilize with balloon pump therapy, a ventricular assist device is the next course of progressive therapy.

**VENTRICULAR ASSIST DEVICES**

**Preoperative Considerations**

Indications for ventricular assist devices include unstable hemodynamic measurements and failure to stabilize measurements with other less invasive therapies previously discussed. Common hemodynamic parameters that are indications for a ventricular assist device placement are listed in Table 122.1. In the preoperative assessment, it is important to determine the likelihood that right ventricular support will be needed as a course of therapy. There are several scoring systems that are commonly used (4–6). Most of these scoring systems center on the calculation of right ventricular stroke work and other hemodynamic indices. Generally, practitioners should use caution if the central venous pressure is greater than the pulmonary capillary wedge pressure, or if the patient’s central venous pressure is greater than 20 mm Hg after optimization. Dependence on the right ventricle to support a left-sided device in such instances may prove to be difficult. It is also important to look at the overall illness of the patient. Patients who are very debilitated at the time of implantation, with organ deterioration caused by right heart dysfunction, are more likely to require right-sided support devices. Thus, it is important to take elevated liver enzymes, abnormal coagulation parameters, and renal dysfunction into consideration.

Finally, it is important to select the device based on the goal of implantation. Devices may be implanted as a bridge to recovery, a bridge to transplantation, or as a destination therapy. The lines between bridge to recovery and bridge to transplantation can sometimes become blurred when the neurologic status of patients cannot be defined prior to implantation. These patients have been termed bridge to decision, where a short-term device may be appropriate to stabilize hemodynamics until the neurologic status and overall candidacy for transplantation is better elucidated. Finally, in patients who are not candidates for transplantation because of age or end organ dysfunction, consideration of destination therapy may be appropriate. Destination therapy refers to permanent device implantation, intended to remain in use for the duration of the patient’s lifetime.

**Preparation of the Patient**

Before the operative implantation of the ventricular assist device, it is often useful to have a period of volume optimization, or a preoperative “tune up.” This is done to ensure that right ventricular function is as well preserved as possible for placement of a left ventricular assist device. This may include diuretic and inotropic therapy. In some cases, where the decision for biventricular support is difficult, a 24- to 48-hour period of intra-aortic balloon pumping may be a useful prognostic indicator. This helps to demonstrate the response of the right ventricular function to a reduced left ventricular end-diastolic pressure (7). During this period of optimization, it is ideal to use an arterial pressure monitor and a pulmonary artery catheter to allow fine tuning of medications and volume status.

It is essential that attention be given to antimicrobial prophylaxis during the period of preoperative optimization. This usually involves selective skin decontamination with Hibiclens scrub (Regent Medical, London, UK). Additionally, Bactroban (mupirocin) is often used to reduce the number of pathogens in the nasal passages of the patient. It may also be useful to use red cell augmentation in patients who are having semi-elective implants, as frequently there may be a 5- to 7-day delay before implantation, during which time erythropoiesis-stimulating drugs, such as erythropoietin, can be combined with iron supplementation to achieve a significant increase of hematocrit.

**Classification of Ventricular Assist Devices**

**Flow Type**

The devices may be classified by the type of flow:

- **Pulsatile**: In these devices, the intermittent relocation of a pusher plate or blood sac emits a pulsatile wave similar to that of the natural heart (Fig. 122.5).
Axial flow: The term nonpulsatile is frequently applied to these devices, although this is a misnomer. These pumps actually have a central blade that rotates at a rapid rate, similar to a jet engine in an airplane (Fig. 122.6). The native function of the left ventricle does intermittently augment the inflow to the pump, which generates a pulsatile output at appropriate speeds.

Centripetal flow: These pumps have a continuous spinning impeller that generates a flow similar to axial pumps. However, the more advanced pumps, currently in development, may be magnetically levitated to function without bearings (Fig. 122.7).

Mechanism

Pneumatic: These pumps are operated by air, where intermittent external application of compressed gas through a tube to a blood sac emits the pulse of the pump (Fig. 122.8).

Electric: Electric pumps are driven by batteries or AC current via an adapter. They may have the axial flow motor, or the pusher plate-driven motor (Figs. 122.5 and 122.6).

Location

Paracorporeal: These pumps are placed outside of, but in continuity with, the body, usually connected via transcutaneous cannulas that are surgically implanted into the heart (Figs. 122.8 and 122.9).

Intracorporeal: This term typically refers to those pumps that are placed completely within the body with only a drive line exiting the skin (Fig. 122.10). The main pumping mechanism is within the body, rather than external to it.

Potential Duration of Support Based on Device Type

Short term: These devices are placed to resolve immediate hemodynamic instability as either a bridge to recovery, a bridge to decision, or for use during a short-term procedure. Their use is intended for hours to weeks.
Medium term: These devices are inserted with the intention of allowing recovery of the native heart function, or as a short-term bridge to transplantation. They are indicated for weeks to months.

Long term: These devices are intended to be used for either long-term bridge patients who will require an extended period of time to acquire donor hearts, or for those patients who may potentially have the device as destination therapy.

**Important Implications for Potential Emergency Situations while the Patient Is Supported by Ventricular Assist Devices**

It is important to understand the physiologic implications of each ventricular assist device, not only while they are in use, but also during periods of unintended pump arrest. One of the critical differentiations between the various types of pumps is the presence or absence of valves and the potential for retrograde flow during periods of pump stoppage. In the devices with valves, a pump arrest merely means that the augmented flow no longer exists, and the presence of valves should prevent retrograde flow. This is a key point to consider during emergency management. The pumps with no valves, such as the axial flow devices, will allow volumes in excess of 1.5 L per minute of retrograde flow during periods of pump arrest. This degree of acute aortic insufficiency will frequently lead to ventricular arrhythmias and cardiovascular collapse.

Knowledge of these internal components and working mechanisms leads to proper decision-making during emergencies. Health care providers must know whether the pump can be temporally actuated via an external mechanism (blood sac pumps) by an individual (as opposed to the driver), and whether or not the pump electronics are defibrillation-compatible.

**FUTURE DEVICES**

Although this chapter is not intended to be comprehensive of all devices currently in development, a few general trends are relevant. Most future generations of these devices are currently being designed to have a longer life span so that they are better suited for destination therapy. Enhanced battery life will allow for greater independence, and a reduced need for transcutaneous attachment to the device, thus reducing infectious complications. Additionally, to extend the life span of these devices, future development will focus on total elimination of bearings and metal-to-metal contact through magnetically levitated bearingless designs. Currently, the primary vulnerabilities of such devices remain issues of anticoagulation and thromboembolic events.
Chapter 122: Cardiac Mechanical Assist Devices

Management of the Post–Left Ventricular Assist Device Patient

Most ventricular assist device (VAD) centers strive to support patients with left-sided devices only and limit the number of patients who require right ventricular assist devices whenever possible. Patients on single ventricular support are more mobile and more rapidly rehabilitated. Thus, a major focus of post-left ventricular assist device management is the stabilization of right heart function and prevention of right heart failure. To accomplish this goal, the most important factor is the selection of patients who have sustainable right ventricular hemodynamic parameters preoperatively. The previously discussed period of optimization often allows patients with marginal right ventricular function to have significant improvement. This is crucial and ranks just under the requirement that the right heart can support the function of the left ventricular assist device. Additionally, right heart function is frequently supported for some period of time with inotropic therapy. The most commonly used drugs are dobutamine or a phosphodiesterase inhibitor such as milrinone (7). Aggressive attempts are made to lower the pulmonary artery resistance by using nitroso-dilators, such as sodium nitroprusside, nitroglycerin, and inhaled nitric oxide. There is some enthusiasm for the use of inhaled prostacyclin as a less expensive alternative to inhaled nitric oxide (8,9). Other more novel options in evolution include the use of orally available, direct-acting drugs on the pulmonary vasculature, such as the use of sildenafil, a phosphodiesterase type 5 inhibitor (10,11).

After placement of a left ventricular assist device, meticulous care of the drive line site is important to reduce the risk of ascending infection. This typically involves diligent immobilization of the drive line and the use of topical treatments, initially several times a day. In cases where infection is noted at the drive line site despite all efforts, topical treatments can be used with success (12).

Dysfunction and Complications of Left Ventricular Assist Devices

- **Cannula kinking:** In the paracorporeal devices, this is particularly problematic. Shifting of patient position or rolling in the bed can lead to either dislodgement or, more frequently, kinking of the transcutaneous cannula. This will lead to flow alarms and sudden dysfunction of the device, and can usually be addressed by simply removing the kink in the cannula. Often, centers have found it beneficial to keep a folded towel under the device to keep it off the patient’s skin and to keep the cannulas straight. With the intracorporeal devices, this problem is usually secondary to device migration, either from chest closure in the operating room or from postoperative ambulation. With intracorporeal devices, this frequently requires reoperation for adjustment of the device.

- **Thrombosis and embolism:** The Achilles heel of all device therapy remains the poorly understood human coagulation system and the effects of foreign bodies in the bloodstream. Depending on the specific device selected and the type of...
valves within the device, variable amounts of anticoagu-
lant are recommended by the manufacturer. Regardless of
the anticoagulant used, thrombus, embolism, and bleeding events are a concern with all devices. It is im-
portant to treat patients with any new symptom, such as
abdominal pain or a cold leg, as if it were a thromboem-
boic event. With appropriate management of anticoagu-
lant and diligent patient care, these events are relatively
infrequent.

Mechanical device issues: The devices themselves may have
mechanical issues related to valve dysfunction or problems
with either bearings or motor wear. These are addressed in
the materials supplied by the manufacturers. All of the de-
vices require some type of ongoing surveillance and assess-
ment for wear and potential mechanical failure.

Patient foramen ovale and hypoxemia following left ventric-
ular assist placement: Patients need to be carefully screened
in the operating room with transesophageal echocardiog-
raphy and provocation maneuvers during a bubble test to
identify a patent foramen ovale. With the altered hemody-
namics following left ventricular assist device placement, the
left atrial pressure is suddenly dramatically lower than the
right atrial pressure. This allows even the smallest patent
foramen ovale to become clinically significant, with right-
to-left shunting occurring and resulting in hypoxemia. A
recent report described partial digital occlusion of the main
pulmonary artery as a provocative maneuver to be used dur-
ing the bubble study (13). Such a maneuver enhances the
intraoperative detection of patent foramen ovale during de-
vice placement. A patent foramen ovale discovered in the
operating room prior to placement of the ventricular assist
device and those discovered after the device is activated in
the operating room should be closed at that time. There are
some reports of patients being treated with percutaneous
device closure, when discovered as a cause of persistent hy-
poxemia several hours or days following device placement
(14).

Right heart failure and the potential need for a right ven-
tricular assist device: One of the greatest concerns when im-
planting a left ventricular assist device is the potential need
for right ventricular assist device therapy. This risk can be
minimized by careful adherence to the post–left ventricular
assist device management protocols discussed earlier in the
chapter. However, despite best efforts, a small percentage of
patients will still develop refractory right heart failure neces-
sitating device therapy. If this occurs in the operating room, it
is possible to use temporary support of the right heart while
the cardiopulmonary bypass cannulas are still in place. This
is done by using a Y off the arterial line and clamping the
line to the aorta, thus redirecting blood flow from the pump di-
rectly into the pulmonary artery via a separate cannula. This
sets up a circuit in which the blood is drawn from the right
atrium, oxygenated by the cardiopulmonary bypass circuit,
and then returned to the pulmonary artery. The effect of su-
peroxygenated blood on the pulmonary artery may result in
a reduction in pulmonary resistance over several minutes
and obviate the need for a right ventricular assist device.
This is often referred to as a Berlin bridge and may be a ben-
eficial intermediate step before placing a right ventricular
assist device when right ventricular dysfunction is apparent
in the operating room. When right heart dysfunction and
failure develop several days after a left ventricular assist de-
vice placement, some type of short-term device support may
be required if the heart remains refractory to initial inter-
terventions. These interventions include the multiple levels of
pharmacotherapy previously discussed.

Bleeding: One of the most common complications related
to ventricular assist device therapy is bleeding. This is most
common during the perioperative period, but can also oc-
cur with anticoagulation during device use. Individual insti-
tutions must make the decision regarding the appropriate-
ness of aprotinin therapy. It has been our standard practice
to use a full dose of aprotinin (full Hammersmith proto-
col, see package insert) at the time of device implantation
and with subsequent transplantation because of the tremen-
dous importance of hemostasis. At the time of the second
exposure, a test dose is administered only when cardiopul-
monary bypass is immediately available because of the risk
of a hypersensitivity reaction. Additionally, it is imperative
that meticulous hemostasis be obtained and maintained dur-
ing ventricular assist device therapy. The administration of
blood products, especially plasma and platelets, increases
pulmonary resistance. This increased resistance, in combi-
nation with the volume associated with these products, can
precipitate right heart failure. This outcome should always
be considered when using blood product therapy.

Patient factors: These factors include the patient factors of
devices such as accidental disconnects, where a patient, in
spite of optimal education from physicians and VAD staff,
simultaneously disconnects all power sources to their de-
vice, resulting in pump stoppage. Additionally, traction in-
juries are common. Particular attention should be given to
entering and exiting vehicle doorways, as these seem to be particularly problematic for
the drive lines of ventricular assist devices.

TRANSITION FROM ICU TO THE FLOOR AND OUTPATIENT MANAGEMENT

It is beyond the scope of this chapter to discuss personnel man-
agement. However, dedicated staff members are essential and
must be thoroughly trained to deal with outpatient manage-
ment of ventricular assist devices. Communication and current
knowledge of the device is paramount to the success of the
ventricular assist device program. This requires the establish-
ment of community resources and alternate caregiver training
so that there is redundancy at every level of the system. Al-
though minor problems with these patients and their devices
are not uncommon, most are easily handled if the support staff
are prepared and adequately trained. Mechanical assist devices
can enhance not only the quantity, but also the quality of life
for these patients.

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**IMMEDIATE CONCERNS**

Critically ill patients with valvular heart disease (VHD) presenting to the intensive care unit (ICU) fall into three primary categories: (a) patients who are critically ill as a result of acute onset, newly acquired VHD; (b) patients with exacerbation or complications of pre-existing VHD; or (c) patients with concomitant VHD who are critically ill from other causes. Most patients present with instability secondary to left heart valvular disease, which, if severe, impairs right heart function, but in patients, right heart valvular lesions can be the predominant problem. Hemodynamic consequences of decompensated left-sided valvular lesions include diminished cardiac output with tissue hypoperfusion, and pulmonary venous hypertension with pulmonary edema that, if severe, leads to pulmonary arterial hypertension and right heart failure. Isolated right-sided valvular lesions present with reduced cardiac output and systemic venous congestion. Management is determined by the type of lesion and its hemodynamic consequences, and is modified by coexisting derangements. Noninvasive assessment of the hemodynamic derangement by history, physical exam, chest radiography, or transthoracic echocardiography (TTE) is essential, but useful information may also be derived from invasive measurements such as arterial blood pressure, cardiac filling pressures, cardiac output, mixed venous oxygen saturation, and calculated cardiovascular variables such as left ventricular stroke work index, systemic vascular resistance, and pulmonary vascular resistance. Invasive monitoring is particularly useful for guiding and assessing the results of management.

Patients with life-threatening valvular disease generally present to the critical care unit with one or more manifestations of congestive heart failure that require immediate sta-

**CRITICAL ILLNESS CAUSED BY VALVULAR HEART DISEASE**

Although valvular disease is often known from the patient’s history, detection by physical examination may be made difficult by environmental noise, pulmonary rhonchi, or other factors. Further, with severe aortic or mitral stenosis and a failing left ventricle, cardiac murmurs may be unimpressive or even absent. Electrocardiography frequently reveals the existence of concomitant ischemic heart disease, left ventricular hypertrophy, atrial abnormalities, arrhythmias, or right ventricular hypertrophy. Portable plain film chest radiography...