A left ventricular assist device (LVAD) is intended for use as a temporary bridge to transplantation in patients with end-stage cardiac failure until a donor heart becomes available. This case report discusses the anesthetic management of a patient undergoing implantation of an LVAD.

Tremendous advances have been made in cardiac transplantation; however, there is an acute donor shortage in the face of an increased need for donor hearts. These two factors have been the impetus for the development and testing of a mechanical assist device. A new U.S. Food and Drug Administration approved assist device, the Thermo-Cardiosystems, Inc. (Woburn, Massachusetts) implantable pneumatic LVAD is proving to be very successful as a bridge to transplantation.

A case is presented of a 40-year-old male with debilitating cardiomyopathy in conjunction with mitral regurgitation, pulmonary hypertension, and mild tricuspid regurgitation. He had reached the point of multisystem organ failure which had left him incapacitated while awaiting cardiac transplantation.

Key words: Bridge to transplantation, cardiomyopathy, end-stage cardiac disease, left ventricular assist device (LVAD).

Introduction
Cardiac transplantation is the preferred treatment option for patients with end-stage cardiac disease. Each year some 15,000 Americans die before suitable organs can be found. In the United States alone, the annual patient population in need of cardiac transplant is currently between 15,000 and 30,000. Unfortunately, there are only 2,000 to 3,000 potential hearts available annually to this entire population.

A multifold problem has developed. Technology, as well as preventive medicine, has reduced the incidence of those patients dying from heart disease; however, the underlying disease process is not being cured. This slowed disease progression, combined with a preexisting donor shortage, has resulted in an increased number of transplant candidates in the United States for a limited pool of donor hearts. At this point, the only solution is to rely on mechanical systems: total artificial hearts, left ventricular assist systems, right ventricular assist systems, or intra-aortic balloon pumps. Although the intra-aortic balloon pump may be used as a bridge, it often cannot provide adequate support for patients whose hemodynamic status deteriorates while they are awaiting transplantation. In addition, an intra-aortic balloon pump cannot normalize or even improve end-organ dysfunction as a left ventricular assist device (LVAD) can.

The indication for LVAD placement is the progressive deterioration of cardiac function despite maximal pharmacological and/or intra-aortic balloon pump support. The most important role of mechanical support is the prevention of hypoperfusion leading to multiple organ failure. U.S. Food and Drug approved indications for LVAD placement are an approved transplant candidate who exhibits any one of or a combination of the following: currently on inotrope support, on an intra-aortic balloon pump, and has a pulmonary capillary wedge pressure greater than 20 mmHg with either a systemic blood pressure of less than 80 mmHg or a cardiac index of less than 2.0 L/min per m². The relative indications for implantation of an LVAD are congestive heart failure, elevated
pulmonary artery pressures, and renal insufficiency that becomes resistant to medical therapy.

**Technical aspects of left ventricular assist devices**

Two different types of assist devices exist which augment the function of the right or left ventricles. They are categorized as either pulsatile or nonpulsatile. Functionally, they all pump against an afterload at physiologic flow rates.\(^7\)

Pulsatile pumps function as pneumatic blood sacs to which external pressure is applied during ejection to force blood into the arterial tree.\(^7\) These blood sacs are compressed by programmed pulses of pressurized air that are generated by an external drive unit that is connected to the ventricle by air lines (Figure 1). During systole the blood sac is squeezed by the increased gas pressure within the pump case.\(^7\) Negative pressure is not directly applied; it is created passively when air in the system is shuttled out of the pump. The pump fills by gravity drainage, i.e., it is volume dependent and does not "draw" blood into it (Figure 2). The Heartmate® LVAD (developed by Thermo-Cardiosystems, Inc., Woburn, Massachusetts) is an example of a pulsatile, pneumatic pump.

Nonpulsatile pumps are centrifugal in their function. This type of pump causes a rotational acceleration of the blood by means of a spinning impeller powered by an electric motor.\(^7\) Because this pump produces a flow by rotational acceleration, the resultant pressure is not pulsatile. Examples of a centrifugal pump would be the BioMedicus, Medtronic, and Sarns. In this paper, only pulsatile pumps will be examined.

**Specifications of the Thermo-Cardiosystems, Inc. Heartmate**

Of the numerous pulsatile LVADs under investigation, the implantable Heartmate seems to have a distinct advantage because it is designed for longer use with minimal risk.\(^4\)

The Heartmate is a totally implantable, pneumatically driven device.\(^8\) The pump is placed in the left upper quadrant of the abdominal wall and attached to a portable console. The inflow conduit penetrates the apex of the left ventricle and crosses the diaphragm to the pump, hence draining the left ventricle. The outflow cannula is anastomosed to the ascending aorta into which blood is ejected. Both inflow and outflow conduits have unidirectional porcine xenograft valves incorporated into them (Figure 3). The pump dimensions are: diameter, 11.2 cm; height, 4.0 cm; and weight, 570 g.\(^9\) Because of the size of the device, the potential candidate must have a body surface area of 1.5 m\(^2\) or...
greater to allow placement of the device in the intra-abdominal cavity. The pump has a stroke volume of up to 83 mL and is capable of a flow of 10 L/min. Up to 40 minutes of support can be provided on battery.

The interior surface is created from either integrally textured polyurethane or sintered titanium microspheres, which are designed to encourage the formation and adherence of pseudoeointimal biological lining. The pseudoeointimal lining functions as a permanent, biocompatible blood contacting surface.

This case study discusses and details the case of a patient with severe end-stage cardiomyopathy with multisystem organ involvement. Indications for the use of an LVAD and its functions are reviewed. Preoperative anesthetic management, intraoperative anesthetic care, and postoperative considerations for the patient with implantation of an LVAD are discussed. The objective is to facilitate the understanding of LVADs and provide the anesthesia caregiver with the knowledge needed to provide an effective plan of management.

**Preliminary patient findings**

A 40-year-old white male weighing approximately 80 kg with a body surface area of 1.97 m² was admitted to the coronary intensive care unit with a diagnosis of congestive heart failure secondary to severe mitral regurgitation.

A pulmonary artery catheter was placed with initial pulmonary artery pressures of 60/28 mmHg, cardiac output 5.48 L/min, cardiac index 2.84 L/min per m², central venous pressure 22-28 mmHg, and a systemic vascular resistance of 910 dynes•sec/cm⁵. These values, although appearing somewhat acceptable, were not considered accurate due to his severe regurgitation.

Pertinent laboratory data included an elevation of his blood urea nitrogen and creatinine attributed to longstanding renal insufficiency exacerbated with congestive failure. An increase in his liver function studies was secondary to hepatic congestion. A resting multigated acquisition (MUGA) scan demonstrated the left ventricle to be dilated with global hypokinesis due to severe mitral regurgitation. The left ventricular ejection fraction was abnormal at 34%. The right ventricle was noted to be mildly enlarged and demonstrated a depressed systolic function. Both atria were enlarged. Cardiac catheterization confirmed the noted valvular disease and the coronary arteries were patent without stenosis. Chest roentgenograms showed marked pulmonary congestion with a right upper lobe infiltrate. His electrocardiogram showed VVI pacing with 100% capture. Thirteen years ago he had surgical ablation of his A-V node for Wolff-Parkinson-White syndrome in which a VVI pacemaker was implanted.

Attempts were made to medically stabilize the patient while awaiting cardiac transplantation. He was started on dobutamine to decrease his pulmonary and peripheral vascular resistance and augment his cardiac output. Renal dose dopamine was also begun, and sodium nitroprusside was started to reduce his afterload. Diuresis was attempted with bumetanide and zaroxolyn.

Initially he was not considered a candidate for an LVAD because of prior sternotomy. The decision was ultimately made to proceed with the placement of an LVAD based on the fact that his cardiac procedure for A-V node ablation was 13 years ago, the unavailability of a donor-match heart, his instability and poor prognosis, and his young age.
Clinical case report

The patient arrived in the holding area the morning of surgery awake and alert. A 14-gauge intravenous catheter was placed in each arm. In the operative suite, an electrocardiogram (leads II and V), a pulse oximeter, and a blood pressure cuff were attached. Oxygen was supplied via nasal cannula at 4 L/min. He was sedated with fentanyl 100 μg and midazolam 1 mg intravenously. A right femoral arterial line was placed. This site was chosen over the radial artery because of its direct access and proximity to the surgical field. A pulmonary artery catheter was in situ via the right internal jugular vein. Baseline hemodynamic readings included a pulmonary artery pressure of 43/20 mmHg, central venous pressure 28 mmHg, and an arterial blood pressure of 100/60 mmHg. Preinduction cardiac output and index were 7.3 L/min and 3.1 L/min per m² respectively, although these values were not considered valid due to his degree of regurgitation. His monitor pattern exhibited a paced rate of 94 with 100% capture. Dopamine was infused into the pulmonary artery side port at 2 μg/kg per minute along with dobutamine at 25 μg/kg per minute.

Induction of general anesthesia was accomplished with etomidate 10 mg and fentanyl 500 μg. Intubation was facilitated with succinylcholine 120 mg. An 8.0 oral endotracheal tube was placed, and the position was verified by the presence of bilateral breath sounds and capnography.

A transesophageal echocardiogram probe was passed demonstrating 2+ mitral regurgitation, trace aortic regurgitation, and tricuspid regurgitation.

A fentanyl infusion was initiated at 0.125 μg/kg per minute. A midazolam infusion was begun at 0.5 μg/kg per minute. Oxygen was combined with 0.5 FiO₂ to provide an FiO₂ of 50%. End-tidal isoflurane was maintained between 0.2%-0.4%. Pancuronium was administered at a dose of 0.05 mg/kg.

One gram of cefazolin was administered intravenously prior to midsternotomy. A test dose of 1 mL of aprotinin (1.4 mg or 10,000 kallikrein inhibitor units or KIUs) was also administered. After 10 minutes when no adverse effects were noted, the patient was given 200 mL of aprotinin over 20 minutes. After this infusion was complete, he was administered 40 mL of aprotinin hourly until the end of the case. The cardiopulmonary bypass system was also primed with 200 mL of aprotinin.

The patient was heparinized with 30,000 units of heparin and then cannulated. He remained hemodynamically stable until cardiopulmonary bypass was initiated. Once bypass began, O₂/air flows were lowered to 1 L/min each. Isoflurane was discontinued via the anesthesia circuit and restarted through the bypass machine once stabilized on extracorporeal circulation. The fentanyl and midazolam infusions were maintained at 0.125 μg/kg per minute and 0.5 μg/kg per minute respectively. Pancuronium was continued at 0.025 mg/kg. The dobutamine was discontinued and dopamine remained at renal dose. Phenylephrine was begun at 8 μg/min to treat a decline in the mean arterial pressure (MAP) due to hemodilution with the initiation of bypass. The MAP sagged to 40 mmHg during transition to calculated flow cardiopulmonary bypass. Despite doubling the phenylephrine concentration, the MAP could not be maintained above 60 mmHg. Norepinephrine was started at 20 μg/min, and the MAP was then maintainable at 60 mmHg and above.

The Thermo-Cardiosystems, Inc. Heartmate LVAD was placed into the patient as previously described. He was then rewarmed and once spontaneous cardiac rhythm started, the LVAD was de-aired. The patient was successfully weaned from bypass to the LVAD. The LVAD was observed to be functioning well on echocardiogram and the device delivered a cardiac output of 5 L/min. Satisfied that all bleeding was controlled, 250 mg of protamine was administered. The total cross clamp time was 62 minutes, and total cardiopulmonary bypass time was 186 minutes. Postpump pulmonary artery pressures ranged from 23/12 mmHg to 28/18 mmHg. The central venous pressures were reduced from a prepump high of 28 mmHg to postpump of 17 mmHg.

Once bypass was terminated, the patient was transfused with 6 units of fresh frozen plasma, 10 units of platelets, 10 units of packed red cells, and 1,600 mL of blood from the cell saver. A total of 4,000 mL of crystalloids were administered. The blood loss was estimated at 3,100 mL and the urine output was 640 mL. The patient was transported to the surgical intensive care unit in stable condition. He required inotrope support during transport in the form of norepinephrine at 8 μg/min and epinephrine at 2 μg/min.

Discussion

Most potent inhalational anesthetic agents have a vasodilatory effect. One must consider organ/tissue perfusion and the end-product of hypotension in association with the anesthetic agents used in the cardiac surgical patient. Add to this complexity the hepatic degradation of agents, renal clearance, systemic and pulmonary vascular effects, and cardiac system alterations.

The psychological components of the patient's physiological condition in relationship to the pro-
posed surgery must also be considered. Their debilitating cardiac disease has usually rendered them inactive and dependent upon others for care. Altered states of body image with implantation of an LVAD will have a direct psychological impact.

To be considered safe, the device must be reliable and must not jeopardize the ability to perform the transplantation in the patient; that is, the device should not be associated with unacceptable levels of adverse effects such as bleeding, infection, hemolysis, end-organ dysfunction, or thromboembolic complications. To be considered effective, the device must improve the hemodynamic status of the patient, enhance the likelihood of survival, and ideally promote a higher quality of life than would be possible without the device.

**Anesthetic considerations**

- **Preoperative.** The patient undergoing implantation of an LVAD is gravely ill and generally exhibits some degree of multisystem failure. This is due in part because the organ systems involved complement one another via autoregulatory and feedback mechanisms. The function or dysfunction of one organ system can directly affect the function or dysfunction of another. A proper evaluation enables the anesthetist to fully understand the overall condition of the patient in anticipation of any intraoperative problems that may arise.

  A thorough history should be obtained by interviewing the patient and/or family member. The preoperative evaluation should include the standard criteria involved in evaluating any patient for cardiac surgery; however, four organ systems should be given special consideration.

  Assessment should obviously begin with the patient's cardiac status. The patient should be evaluated for any structural heart diseases, myocardiopathies, coronary artery disease, and diseases of the conducting system. Past history involving myocardial infarction, congestive heart failure, and pulmonary edema should be obtained. All associated symptomatology should be reviewed as to whether they occur at rest or are exercise induced.

  From a pulmonary standpoint, it should be determined if the patient has a prior smoking history, a history of recurrent respiratory infections, or exposure to noxious inhalants. It is also necessary to monitor arterial blood gases and have the acid-base status regulated prior to surgery and any deficits optimized.

  The renal system is of concern because patients undergoing cardiopulmonary bypass have a large fluid load typically administered with a crystalloid bypass prime. Also, potassium is usually a part of the cardioplegia solution.

  The patient should be evaluated for any hepatic dysfunction. Of prime importance is any history of hepatitis or clotting abnormalities. Patients with liver dysfunction often have an elevated prothrombin time due to deficits of clotting factors. Transfusion of fresh frozen plasma may be considered preoperatively, but fluid overload should be avoided. Another consideration is the biotransformation of anesthetic agents in the liver. In any patient with hepatic dysfunction, a slowed drug metabolism or prolonged duration of action could occur.

  The patient must also be typed and crossmatched for 6 units of cytomegalovirus negative blood. Cytomegalovirus negative blood is used to ascertain that the patient will be at a reduced risk of infection following cardiac transplantation, because of the necessity of immunosuppression.

  Premedication may include some of the patient's cardiac medications. If the premedicant includes an opioid, it should be administered with caution because hypotension could have deleterious effects.

- **Intraoperative.** The induction of anesthesia is one of the most critical periods for the cardiac patient. The goal is to render the patient unconscious, analgesic, amnestic, and motionless to allow passage of an endotracheal airway while maintaining stable hemodynamics. To obtain this goal, the anesthetist must anticipate the interaction between the patient's physiologic findings, anesthesia, normal reflex responses, and abnormal patient airway anatomy.

  Etomidate was our induction agent of choice. This drug has been proven to be beneficial for the cardiovascular surgical patient because it preserves hemodynamic stability, depresses myocardial metabolic rate, causes no decrease in hepatic or renal perfusion, causes no release of histamine, and produces less hypotension than pentothal. The induction dose of etomidate is 0.3 mg/kg, but in patients with marginal cardiac function it may be titrated at 0.1-0.2 mg/kg.

  Fentanyl is also used as an adjunct in induction because of its cardiovascular stability. It too produces no myocardial depression or histamine release. The recommended dose for intravenous bolus is 5-40 μg/kg. For the maintenance of anesthesia, a fentanyl/midazolam infusion technique was employed, supplemented with a low concentration of isoflurane. As an anesthetic supplement, a fentanyl infusion can be delivered at 0.025-0.25 µg/kg per minute. Midazolam is beneficial in the cardiac patient because it can decrease peripheral vascular resistance and blood pressure and affords good amnesia. Midazolam has a more rapid onset,
a shorter duration of action, and greater amnesic effects over diazepam. Infusion rates can be adjusted between 0.25-1.5 μg/kg per minute.

As our inhalational agent, isoflurane may have several advantages in the cardiac patient over other halogenated compounds. It may cause less myocardial depression, lowers the systemic vascular resistance, and undergoes minimal biodegradation causing less organ toxicity. Pancuronium was our muscle relaxant of choice because of its vagolytic and sympathomimetic effects and lack of histamine release. The use of pancuronium in cardiac patients should be guarded because reflex tachycardia is sometimes not a desirable effect; however, its ability to increase mean arterial pressure and cardiac output by activation of the sympathetic nervous system may actually sometimes be a benefit to hemodynamics.

Cardiac anesthesia can seldom be administered without the concomitant use of vasoactive drugs. At our institution, we use phenylephrine to treat hypotension and nitroglycerin for hypertension prior to cardiopulmonary bypass. We attempt to maintain a systolic blood pressure of at least 110-120 mmHg prebypass and 90-100 mmHg during cannulation. Maintaining the systolic pressure around 100 mmHg is essential during cannulation to prevent aortic dissection. Phenylephrine is desirable not only for its direct alpha1 effects but also because of its short duration of action. Any agent that will affect hemodynamic parameters for an extended period of time due to a long half-life could have an impact on the entire perioperative period. Norepinephrine was utilized when no response was obtained from phenylephrine, even after doubling the concentration. Norepinephrine may be effective when phenylephrine is not due to its intense alpha1, alpha2, and beta2 actions.

Epinephrine was our inotrope of choice upon weaning from cardiopulmonary bypass and maintenance of arterial pressure postbypass. It is desirable because of its purely direct activity. Amrinone was not a consideration at this point due to its potential to produce hypotension.

Patients subjected to cardiopulmonary bypass develop adverse changes of their blood components, blood cells, and coagulation proteins. These changes may cause a deleterious effect during the intraoperative and immediate postoperative period which may result in diffuse bleeding. These changes are of particular concern in the cardiac surgical patient undergoing future secondary cardiac procedures in which multiple blood transfusions and/or surgical reexploration may be required.

Aprotinin is a serine protease inhibitor that inhibits several proteolytic enzymes such as plasmin and kallikrein, thus directly affecting the coagulation cascade and polypeptide mediated inflammatory response. Aprotinin also preserves the adhesive glycoproteins in the platelet membrane. This makes the platelets resistant to damage from mechanical injury associated with cardiopulmonary bypass. The primary goals are to inhibit fibrinolysis and the preservation of clotting factors, which will decrease bleeding. Aprotinin is administered to provide an environment conducive to clot formation and retention following the administration of protamine.

Of final note, a very crucial point in being able to wean from cardiopulmonary bypass to the Heartmate is the patient's volume status. During separation from bypass, a volume loading (greater then normally needed during weaning), will be required for initiating the Heartmate's support. Again, the Heartmate is volume dependent and a central venous pressure in the 17-19 mmHg range during separation from bypass is needed to initiate Heartmate pumping. The patient's afterload must also be decreased. The pump, because it only shuttles room air to move the pusher plate, cannot pump against a high afterload. A MAP of no greater than 85 mmHg is preferred, 70-80 mmHg is ideal.

Postoperative. Management of the patient undergoing placement of an LVAD extends well into the postoperative period. The patient should be observed for any changes that would be indicative of postoperative bleeding. The level of blood/fluid in the chest tube bottles should be closely monitored. The patient's hemodynamic status should be assessed for any changes in arterial or pulmonary artery pressure readings. The drive line site where it enters the abdomen is assessed for oozing. Blood products, volume expanders, or vasopressors may be indicated to maintain a stable cardiac output and vital signs.

Thromboembolism postoperatively is another concern, but with the design of the Heartmate, this is relatively rare compared to other LVADs. The texture blood contacting surface promotes a biologic interface which functions as a permanent, biocompatible overcoating, reducing the risk of thrombus formation.

Renal perfusion is also monitored for adequate function. Fluid replacement should be calculated to maintain an adequate urinary output. Diuretics or renal dose dopamine may be utilized.

Pulmonary function is compromised by postoperative pain, prolonged anesthesia, incision length, and initial immobility. The inlet conduit of the implanted device that penetrates the dia-
phragm can impede diaphragmatic contractions.

Right-sided heart failure can present a problem postoperatively. Treatment may include the use of prostaglandins and other vasodilators. Temporary support of the right ventricle may also be necessary in the form of a simultaneous right ventricular assist device and/or inotropes and vasodilators.

Infection merits consideration, and measures should be instituted early to avoid this as much as possible. The invasive lines and endotracheal tube should be removed in 72 hours, if possible. The drive line insertion site is the most common source of infection. In postimplantation studies reviewed, enterococcus was the leading organism responsible for sepsis. Second-generation cephalosporins are recommended throughout the perioperative course.

In all of the studies reviewed, mechanical device-related problems occurring postoperatively were relatively rare.

Conclusion
The Thermo-Cardiosystems, Inc. Heartmate implantable pneumatic LVAD has been evaluated as a bridge to transplantation in patients for up to 423 days at seven clinical centers in the United States. In the clinical trials examined, the Heartmate clearly demonstrated its potential for long-term support. Not only did cardiac and other organ function improve dramatically post-implantation, but also survival rate following cardiac transplantation was greater in those individuals who had an IVAD. With the growing shortage of donor hearts available and the expanding success of cardiac transplantation, there will be a definite need for a mechanical bridge to transplantation.

Aftermath to this case
The patient who is the subject of this paper, expired on his 20th postoperative day following complications from pneumonia and renal failure.

REFERENCES

SUGGESTED READING

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