Thirty-Five Years of Mechanical Circulatory Support at the Texas Heart Institute

An Updated Overview

Since the 1960s, the Texas Heart Institute has been intimately involved in the development of mechanical circulatory support devices (for example, ventricular assist devices, aortic counterpulsation pumps, and total artificial hearts) for both short- and long-term use. Here, we review the varied clinical experience with these technologies at the Texas Heart Institute over the last 35 years. (Tex Heart Inst J 2005;32:168-77)

The human heart, about the size of a man’s fist, pumps enough blood in the course of a lifetime to fill the Rose Bowl. The wonderful thing about the heart is that it replenishes itself. To duplicate that mechanically is going to be a very difficult thing to do.

— Denton A. Cooley, MD*

Replacing the failing human heart has had a turbulent history. The 1st human-to-human heart transplantation, performed by Christiaan Barnard in 1967,1 marked an exciting advance in cardiac surgery. It revealed to the medical community at large and to the public that failing hearts could be replaced, at least technically, with healthy ones. However, the initial excitement was quickly overshadowed by the difficulty of managing the attendant immunosuppressive complications. By the early 1970s, only 4 institutions in the world were still performing cardiac transplantation.2 Heart transplantation was reintroduced to a broader surgical population with the advent of the new immunosuppressive agent cyclosporine in the early 1980s.3 This agent spared the nonspecific immune system and allowed the possibility of performing transplantation in patients who required support with mechanical circulatory support (MCS) devices. Before this, 3 patients supported with an MCS device as a bridge to transplant—two with an artificial heart and one with a left ventricular assist device (LVAD)—had died of overwhelming sepsis due to generalized immunosuppression while receiving azathioprine. In March 1984, Frazier performed cardiac transplantation in a young woman who was septic with Staphylococcus aureus and Candida albicans at the time of transplantation. In spite of overwhelming sepsis, she survived the transplantation and was ultimately discharged safely from the hospital.4 This experience, which showed that successful cardiac transplantation was feasible with cyclosporine use even in severely infected patients, stimulated research into the eventually successful use of MCS devices as a bridge to transplantation.

In 1966, DeBakey reported the 1st successful use of a ventricular assist device (VAD) for postcardiotomy support in a patient who was supported by the device for 10 days.5 In 1969, Cooley became the first to implant an artificial heart (which was designed by Liotta) in a human being6 (Table I). Since the 1960s, the Texas Heart Institute (THI) has been involved in the development of other MCS devices, including univentricular and biventricular devices, aortic counterpulsation...
pumps, and total artificial hearts (TAHs). Historically, these devices were used to provide short-term support for patients in cardiogenic or postcardiotomy shock or as a bridge to transplantation. More recently, they have come to be used to provide support during high-risk interventional procedures, as a bridge to recovery, or as destination therapy. Here, we review the varied clinical experience with these technologies at THI over the last 35 years.

**Historical Use of Mechanical Circulatory Support at the Texas Heart Institute**

Since 1969, VADs or TAHs have been implanted in 576 patients at THI. An abdominal left ventricular assist device (ALVAD), the TECO Model VII (Thermo Electron Corp.; Waltham, Mass), was used to support 22 patients between 1975 and 1980. The Akutsu model III artificial heart, developed at THI, was implanted in 1 patient in 1981. The Jarvik-7 TAH, designed at the University of Utah College of Medicine and first implanted by DeVries at the University of Utah in 1982, was used at THI in 2 patients in 1986. In 1988, the Hemopump (Johnson & Johnson Interventional Systems; Rancho Cordova, Calif) was first used at THI by Frazier and colleagues and was ultimately implanted in 43 patients over the next 5 years.

**Current Era of Mechanical Circulatory Support at Texas Heart Institute**

**Long-Term Support Devices**

Long-term MCS devices are used as a bridge to transplant, as a bridge to recovery, or as destination therapy. Currently at THI, 6 systems are being used clinically for long-term MCS. These include 5 VADs and a totally implantable artificial heart. Three of these systems are commercially available and 3 are investigational.

**HeartMate® IP LVAS**

The HeartMate implantable pneumatic left ventricular assist system (HeartMate IP LVAS, Thoratec Corp.; Pleasanton, Calif) (Fig. 1) is a pulsatile blood pump that provides left ventricular support. The HeartMate IP is used in patients as a bridge...
Mechanical Circulatory Support at THI

to transplant or bridge to recovery. The system consists of a pusher-plate blood pump, an interconnecting drive line, and an external drive console. The pump is positioned in the upper left abdominal quadrant, either intraperitoneally or preperitoneally. A percutaneous drive line attached to an external console delivers pulses of air that cause the pusher-plate and diaphragm to eject blood from the pump. A sensor, located in the lower housing of the blood pump, monitors the position of the diaphragm in order to determine the stroke volume. The pump can produce a stroke volume of 83 mL and flows of up to 11.5 L/min.

The Texas Heart Institute has been involved in research and development of the HeartMate LVAS technology for more than 30 years. In 1978, the 1st clinical trial of a predecessor of the HeartMate, the Model 7 LVAD, was initiated in 20 postcardiomyopathy patients at THI. The 1st clinical trial of the HeartMate IP LVAS began in 1986, also at THI. The initial trial was expanded to 17 centers in the late 1980s and early 1990s. In 1994, the US Food and Drug Administration (FDA) granted marketing approval for the HeartMate IP LVAS as a bridge to transplant. The HeartMate IP LVAS has been implanted in 87 patients at THI. Since the development of an electrically driven version of the HeartMate (described below), use of the pneumatic version at THI has decreased considerably. Nevertheless, our experience has demonstrated that the HeartMate IP LVAS is highly reliable for extended periods.

HeartMate® VE and XVE. The HeartMate vented electric LVAS (HeartMate VE LVAS; Thoratec Corp.) and an improved version called the HeartMate extended vented electric LVAS (HeartMate XVE LVAS) (Fig. 2) are very similar to the HeartMate IP LVAS. The major difference between the IP device and the VE devices is the method of actuation. The HeartMate XVE is driven by an internal motor that requires 12 V of direct-current power. The motor controls the pusher-plate and diaphragm within the pump. This system is used as a bridge to transplant, as a bridge to recovery, and as destination therapy. A percutaneous drive line attaches to a controller, which connects to a power base unit. The drive line also has a percutaneous vent tube, the purpose of which is to equalize the pressure in the motor chamber. The HeartMate XVE can be powered for short periods (4–6 hours) by portable batteries, thus providing a distinct advantage over the pneumatic version and allowing more patient mobility.

Clinical trials of the HeartMate VE as a bridge to transplant began in 1991. This was the 1st device that allowed untethered patients to be discharged in order to return home and, in some cases, return to work, while awaiting transplantation. The FDA approved the HeartMate VE as a bridge to transplant in 1998 and approved the HeartMate XVE LVAS for the same purpose in 2001. In light of the encouraging results of the multicenter REMATCH trial, which compared LVAD therapy and optimal medical management in patients ineligible for cardiac transplantation, the FDA approved another slightly modified version of the pump, the HeartMate® SNAP-VE, as destination therapy. In 2003, the HeartMate XVE LVAS was also ap-
proved by the FDA as destination therapy. The HeartMate VE or XVE LVAS has been implanted in 141 patients at THI.

**Thoratec® PVAD.** The Thoratec paracorporeal ventricular assist device (PVAD) system (Thoratec Corp.) (Fig. 3) is a pneumatically driven pump that can provide either univentricular or biventricular support.17

Indications for the Thoratec PVAD include acute heart failure, postcardiotomy shock, and bridge to transplant in cases of end-stage heart failure refractory to maximal medical therapy. The system consists of a blood pump, inflow and outflow cannulas, and a drive console. The external pump and the cannulas rest on the abdomen and connect to the drive console via pneumatic and electric drive lines. The pneumatic console provides alternating negative and positive air pressure that cause the pump’s blood sac to fill and eject blood.18 The pump can produce a stroke volume of 65 mL and flows of up to 7 L/min.

Clinical trials with the Thoratec PVAD began in 1976, and the FDA granted marketing approval in 1995. In 1997, THI began using the Thoratec PVAD in patients requiring right-, left-, or both-sided support for either short or long periods of time. The Thoratec PVAD has been implanted in 89 patients at THI.

**HeartMate® II.** The HeartMate II left ventricular assist system (Thoratec Corp.) (Fig. 4) is an implantable axial-flow blood pump that provides left ventricular support. It is used as a bridge to transplant. The system consists of a blood pump, a system driver, a power base unit, and portable batteries. The blood pump contains a single moving rotor powered by an electromagnetic motor. A drive line, tunneled through the patient’s abdomen, connects to the system driver, which controls the motor. This system uses the same power base unit and portable batteries as does the HeartMate XVE. The HeartMate II has an operating range of 6,000–15,000 rpm and provides up to 10 L/min of continuous cardiac output.18
The Nimbus Corporation began development of the HeartMate II in 1991. The internal components of the device were based on those of the Hemopump—the implantable, catheter-mounted axial-flow pump that was first applied clinically at THI in 1988 but is no longer used. The bearings of the HeartMate II are blood lubricated. The 1st clinical trials were initiated in Europe in June 2000. The initial clinical experience was unfavorable and led to several design changes. The FDA allowed the clinical trial to restart in 2003. The 1st clinical use of the redesigned HeartMate II was at THI in November 2003 in an 18-year-old man who had dilated cardiomyopathy. The patient was successfully rehabilitated and was discharged in April 2004 after the FDA granted permission for study patients to be discharged home to await transplant. The HeartMate II has been implanted in 8 patients at THI and in a total of 42 patients in the United States. Preliminary results indicate that the problems encountered in the initial trial may have been resolved.

Jarvik 2000. The Jarvik 2000 Heart left ventricular assist device (Jarvik Heart, Inc.; New York, NY) (Fig. 5) is an implantable axial-flow pump used for long-term support as a bridge to transplant. The system consists of a blood pump, an external controller, and portable batteries. The blood pump is approximately the size of a C-cell battery and has a single moving impeller in the center of a titanium housing. A power cable, tunneled through the abdomen of the patient, connects to the external controller. Lead acid or lithium ion batteries provide power to the pump. The pump’s operating range is 8,000–12,000 rpm, which can be manually adjusted to provide up to 6 L/min of continuous flow under optimal physiologic conditions. The Jarvik 2000 can be surgically implanted via a midline sternotomy, left thoracotomy, or subcostal (nonthoracic) approach. The various surgical approaches and the small size of the device allow it to be implanted in patients who may not be candidates for support by other LVADs.

Jarvik Heart, Inc., and THI began development of the Jarvik 2000 in 1988. Clinical trials of the Jarvik 2000 as a bridge to transplant began in April 2000. In 2003, the FDA granted permission for patients in that study to be discharged home to await transplant. The Jarvik 2000 has been implanted in 54 patients at THI. Twelve of these patients have been discharged, and one of them has been supported by the device for more than 2 years.

AbioCor™ Total Artificial Heart. The AbioCor TAH (ABIMED, Inc.; Danvers, Mass) (Fig. 6) is a permanently implantable replacement heart system that provides total circulatory support. The AbioCor TAH is currently implanted in patients who are ineligible for heart transplant, have a 30-day predicted mortality of greater than 70% despite maximal medical therapy, and have no other suitable treatment options. The AbioCor system consists of 4 internal components and 4 external components. The internal components include the thoracic unit, a battery, a controller, and a transcutaneous energy transfer (TET) coil. The external components include a TET coil, batteries, a TET module, and a bedside console. The
Thoracic unit consists of an energy converter and 2 pumping chambers that function as the left and right ventricles. Power is provided to the thoracic unit, and the device's internal battery is recharged transcutaneously, by electromagnetic coupling of the internal and external TET coils. The internal TET is positioned under the skin in the upper left or right chest. The external TET is attached with an adhesive to the skin above the internal TET and then connected to the bedside console. Alternatively, power can be supplied to the AbioCor TAH by a pair of portable batteries for up to 60 min. Thus, recipients of the AbioCor TAH may be fully ambulatory. The pump's motor operates at 3,000–10,000 rpm and can generate a flow of up to 8 L/min. One disadvantage of the device is its large size, which limits its use in smaller patients such as women, small men, and children. A smaller version is being developed.

Researchers at THI participated in preclinical trials of the AbioCor TAH from 1993 to 2000. During this period, the AbioCor went through several design changes and was implanted experimentally in 43 calves. In January 2001, the FDA granted permission to begin a multicenter clinical trial of the AbioCor TAH with 15 patients. The Texas Heart Institute is one of 5 centers participating in this initial trial. Five patients at THI and 14 patients overall have received the AbioCor TAH. The longest surviving recipient at THI was supported by the device for 142 days. The longest surviving recipient overall was supported for 512 days.

**Short-Term Support Devices**

Short-term circulatory assistance is often used to support patients in cardiogenic shock or postcardiotomy shock, to provide protection during high-risk procedures, or to serve as a bridge to definitive therapy. Four short-term devices are currently in clinical use at THI.

*BVS 5000®*. The BVS 5000 VAD (ABIOMED, Inc.) (Fig. 7) is a pneumatically driven, pulsatile, extracorporeal, asynchronous pump that can be used for short-term left ventricular, right ventricular, or biventricular support. The device is used primarily as a bridge to recovery in patients who have exhausted all other medical therapeutic options. The BVS 5000...
Mechanical Circulatory Support at THI

The system consists of a dual-chamber blood pump, cannulas, and a drive console. The device is positioned at the patient’s bedside and fills passively by gravity. A bladder within the ventricular chamber is collapsed by pulsed air delivered through drive-line tubing connected to the external console. The BVS 5000 can produce a stroke volume of 80 mL and flows of up to 6 L/min. Clinical trials of the BVS 5000 as treatment for cardiogenic shock began at THI in 1988. The FDA granted marketing approval of the BVS 5000 as a postcardiotomy support device and as a bridge to transplant in 1993. The BVS 5000 has been implanted in 63 patients at THI.

AB5000™. The AB5000 circulatory support system (ABIOMED, Inc.) is similar to the BVS 5000 in that it uses the same drive console and tubing, but different in that its prosthetic ventricle consists of a membrane and 2 trileaflet valves. The indications for its use are the same as those for the BVS 5000. Like the BVS 5000, the AB5000 can produce a stroke volume of 80 mL and flows of up to 6 L/min. In 2003, the FDA granted marketing approval for use of the AB5000 device as postcardiotomy support and as a bridge to transplant. The Texas Heart Institute is one of 20 centers where the device is now being used clinically. The AB5000 has been implanted in 22 patients at THI.

TandemHeart® pVAD™. The TandemHeart pVAD (CardiacAssist, Inc.; Pittsburgh, Pa) (Fig. 8) is a percutaneous, continuous-flow, left ventricular assist device that provides short-term circulatory support. The TandemHeart is used as support during cardiogenic shock, as a bridge to long-term MCS, and for support during high-risk percutaneous coronary interventions. The system consists of a small blood pump, transseptal and arterial cannulas, and a power base controller. The pump contains a magnetically driven rotor supported by a fluid-lubricated hydrodynamic bearing. The TandemHeart can be inserted percutaneously in the cardiac catheterization laboratory or surgically in the operating room. The TandemHeart pVAD typically operates at speeds of 3,000–7,500 rpm and can provide a continuous flow of up to 4.0 L/min.

Development of the TandemHeart began in 1991. In 2002, THI was one of 17 study sites that began enrolling patients in a phase II randomized clinical trial. In July 2003, the FDA granted a 510(k) exemption approving off-study use of the TandemHeart for up to 6 hours in patients who did not meet the study entry criteria. Three patients were enrolled in the trial, and 18 others have been supported by the device under the 510(k) exemption at THI.

Levitronix® CentriMag®. The Levitronix CentriMag (Levitronix LLC; Waltham, Mass) (Fig. 9) is a continuous-flow left ventricular assist device with a magnetically levitated impeller. It can provide circulatory support to patients during cardiogenic shock, as a bridge to long-term MCS, and for support during high-risk percutaneous coronary interventions. The system consists of a small blood pump, transseptal and arterial cannulas, and a power base controller. The pump contains a magnetically driven rotor supported by a fluid-lubricated hydrodynamic bearing. The Levitronix CentriMag can be inserted percutaneously in the cardiac catheterization laboratory or surgically in the operating room. The Levitronix CentriMag can provide a continuous flow of up to 7 L/min and can support patients for up to 7 days.
support for up to 14 days in patients in cardiogenic shock. The system consists of a small blood pump, cannulas, a magnetic motor, and a bedside controller. An advantage of this device is that it can be attached to cardiopulmonary bypass cannulas already in place. The Levitronix CentriMag system is capable of delivering 9.9 L/min of flow at 5,500 rpm. The Texas Heart Institute is one of 5 study sites that is now enrolling patients in a phase I clinical trial that began in 2003. Four patients at THI have been enrolled in the trial, and 13 patients have received the device under a 510(k) exemption.

**Discussion**

The 1st implantation of an artificial heart by Cooley at THI was a last resort to prolong the life of a dying man. After an extensive surgery, the patient's heart could not be weaned from cardiopulmonary bypass. The heart was excised and replaced with a cardiac prosthesis, which supported the patient for 64 hours before a suitable donor heart became available for transplantation. Without the Liotta heart, the patient would have died on the operating table, because a suitable donor organ was not available at the time. These circumstances have been repeated numerous times since 1969. Whether the cause is postcardiotomy failure, cardiogenic shock, or ischemic or idiopathic cardiomyopathy, there is an inevitable point at which the human heart loses its ability to pump blood despite maximal medical therapy.

The clinical indications for MCS continue to expand in step with improvements in technology and patient management. With time, devices are becoming smaller, easier to implant, more reliable, and more efficient. Implantation has been made faster and easier by improvements in design and surgical techniques. In some instances, the smaller axial-flow VADs can be implanted without cardiopulmonary bypass. Because artificial surfaces and valves that come into contact with blood pose an inherent risk of thrombosis and associated complications, the application of most MCS systems still requires concomitant systemic anticoagulation therapy. In some cases, however, the need for anticoagulation and the risk of bleeding complications have been reduced by the use of biocompatible surfaces such as those in the HeartMate VE and XVE. Improved engineering has increased the durability and reliability of MCS devices, although there still remains room for improvement. The increasing need for prolonged pump function is limited not only by the finite mechanical lifetime of the devices, but also by the current inability to provide an efficient, inexhaustible, and portable power source. Most MCS devices require externalization of either a pneumatic or electrical drive line. Although totally implantable systems such as the AbioCor TAH are under development, the internal batteries are able to provide sufficient power only for about 30 minutes. Hence, the transcutaneous transmission of energy from an external source is still required.

There has also been much discussion about the appropriate timing of VAD implantation and the selection of appropriate recipients. Initially, MCS was considered only after all other options had been exhausted. Unfortunately, such a delay might allow multiple organ failure to progress until function is irrecoverable and prognosis is poor. However, recent evidence indicates that MCS may in some cases improve and restore end-organ function and thereby serve as a bridge to recovery. As MCS becomes safer and more effective, it may become possible to place patients on MCS earlier, thus improving their chances of functional recovery. In cases of bridging to transplant, the use of MCS to restore adequate blood flow to organs before they become permanently damaged is critical for improving the prognosis after transplantation. Therefore, the use of MCS at earlier stages in the progression of heart failure will likely become increasingly accepted.

Although bridge to transplant remains one of the principal uses for modern long-term MCS devices, other uses are envisioned as well. Myocardial recovery due to ventricular unloading and workload reduction with a VAD has been noted, especially in patients with acute cardiogenic shock. Reverse remodeling after long-term MCS has been noted too. Nevertheless, explanting MCS devices from a chronically supported patient is still typically performed only under extenuating circumstances such as infection or mechanical malfunction. Further understanding of the phenomenon of reverse remodeling may lead to the use of long-term MCS in selected cases as a bridge to recovery instead of a bridge to transplant.

Increasing experience with MCS has also highlighted the potential use of MCS devices as destination therapy. The AbioCor TAH is presently under investigation as destination therapy in patients who do not qualify for heart transplantation and whose conditions are refractory to optimal medical management. The HeartMate XVE LVAD, which has been in use in some form since the early 1980s, was approved for clinical use as destination therapy by the FDA in 2002. Even axial-flow LVADs such as the Jarvik 2000 and the HeartMate II, which are now being investigated at THI and in Europe as bridges to transplant, show the potential to be used as permanent long-term therapy. Thus far, the experience with the Jarvik 2000 suggests that it may provide reliable support for several years. One patient in Europe has now been supported with a Jarvik 2000 LVAD for over 4 years. Here in the United States, 12 patients supported by
the Jarvik 2000 have been discharged from the hospital, and 1 patient has been supported with the device for more than 2 years.

Several recently introduced VADs provide short-term MCS. Two of them in particular, the TandemHeart pVAD and the Levitronix CentriMag, are now being investigated at THI as part of multicenter clinical trials. The potential clinical indications for short-term support with these devices include cardiogenic shock, high-risk percutaneous interventions, off-pump coronary artery bypass grafting, and bridge to definitive therapy. Both devices are small extracorporeal circuits that can temporarily assume the work of the ventricle.

Our long, single-center experience with the development of MCS devices has imparted valuable information concerning the difficult problem of congestive heart failure. It is clear, for example, that the function of the device must match the needs of the patient and must be applied appropriately. Our early experience with the intra-aortic balloon pump, in which the device was used in 34 patients over a 3-year period before a single patient left the hospital after its application, dramatically illustrates the importance of the suitability and timing of support.27 Today, the mechanism of the intra-aortic balloon pump remains essentially unchanged, and a 70% to 80% survival rate can be expected when this technology is applied to the appropriate patient. The first use of the ALVAD led to a similar observation. The device worked well both experimentally and clinically, but none of the 22 patients who were supported with it survived. This experience aptly reinforces the importance of proper timing of device application and its relationship to patient survival.

Another important observation has been the difficulty of implanting a biventricular pulsatile pump (that is, the TAH). This technology’s current apogee of development is the AbioCor TAH. Its clinical efficiency has been exemplary to date. Nevertheless, the AbioCor TAH remains large and will not comfortably fit within the chest cavity of most candidate patients. Therefore, its minimization with the use of continuous flow technology, used so successfully in LVADs, may play an important role in future clinical applications of the TAH.

Technological improvements and the increasing availability of both short- and long-term MCS devices are broadening the use of MCS. The demand for MCS is increasing as improved medical therapies keep patients with heart failure alive for longer periods of time and as nontransplant surgical techniques for heart failure provide options for many patients who would otherwise require transplantation. Despite medical or surgical management, sick hearts will eventually fail to pump enough blood to meet circulatory needs. Simply replacing failing hearts with healthy ones is not the ultimate solution to heart failure that many thought it would be. Given the widely acknowledged limitations of heart transplantation, MCS may evolve beyond a temporary therapeutic alternative into an accepted long-term, and perhaps even permanent, alternative. In the meantime, further research is warranted to develop MCS devices that more closely duplicate the healthy human heart in terms of reliable function over long periods of time.

References

15. Myers TJ, Dasse KA, Macris MP, Poirier VL, Clay MJ, Frazier OH. Use of a left ventricular assist device in an outpa-


