JACC Vol. 30, No. 7
December 1997:1773–7

Implantable Left Ventricular Assist Devices Provide an Excellent Outpatient Bridge to Transplantation and Recovery

JOSEPH J. DEROSE, JR., MD, JUAN P. UMANA, MD, MICHAEL ARGENZIANO, MD, KATHARINE A. CATANESE, RN, MICHAEL T. GARDOCKI, PA, MARGARET FLANNERY, RN, HOWARD R. LEVIN, MD, FACC, BENJAMIN C. SUN, MD, ERIC A. ROSE, MD, FACC, MEHMET C. OZ, MD, FACC

New York, New York

Objectives. **Our recent experience with outpatient left ventricular assist device (LVAD) support is presented to demonstrate the possibilities and limitations of long-term outpatient mechanical circulatory assistance.**

Background. **The experience with inpatient LVAD support as a bridge to transplantation has proved the efficacy of such therapy in improving circulatory hemodynamic status, restoring normal end-organ function and facilitating patient rehabilitation. With miniaturization of the power supplies and controllers, such mechanical circulatory support can now be accomplished in an outpatient setting.**

Methods. **Between March 1993 and February 1997, 32 patients (26 male, 6 female, mean [±SEM] age 49 ± 15 years) underwent implantation of the ThermoCardiosystems (TCI) Heartmate vented electric (VE) LVAD. The VE LVAD is powered by batteries worn on shoulder holsters and is operated by a belt-mounted system controller, allowing unrestricted patient ambulation and hospital discharge.**

Results. **Mean duration of support was 122 ± 26 days (range 3 to 605), with a survival rate to transplantation or explantation of 78%. Nineteen patients were discharged from the hospital on mean postoperative day 41 ± 4 (range 17 to 68), for an outpatient support time of 108 ± 30 days (range 2 to 466). Four patients underwent early transplantation and could not participate in the discharge program, and three patients currently await discharge. The complication rate was not statistically different from that encountered in our previous 52 patients with a pneumatic LVAD.**

Conclusions. **Outpatient LVAD support is safe and provides improved quality of life for patients awaiting transplantation. Wearable and totally implantable LVADs should be studied as permanent treatment options for patients who are not candidates for heart transplantation.**

(J Am Coll Cardiol 1997;30:1773–7)

Despite improvements in survival with new medical therapeutics, 60,000 patients will eventually develop congestive heart failure unresponsive to any medical therapy (1). Although heart transplantation is an effective treatment for end-stage heart disease, the limited donor pool makes this an option for only 2,500 patients/year (2). As such, heart transplantation has only a trivial impact on the epidemiology of heart failure. In an attempt to fill this void, alternatives to transplantation have been sought, with mechanical circulatory assistance leading the way.

Left ventricular assist devices (LVADs) have been widely and successfully used in the short and medium term as a bridge to transplantation. The now 8- to 10-year experience with LVADs in this setting has established their efficacy in reestablishing circulatory hemodynamic status and restoring normal end organ function (3–5). Aggressive rehabilitation has allowed most of these patients to return to New York Heart Association functional class I heart failure before undergoing heart transplantation (6,7). With the consolidation of the power supplies and controllers, many of these systems have become "wearable" (8,9), thus allowing unrestricted patient ambulation and discharge from the hospital on mechanical circulatory support while awaiting transplantation. Our recent experience with outpatient LVAD support as a bridge to transplantation and recovery is presented to demonstrate the possibilities and limitations of long-term outpatient mechanical circulatory assistance.

Methods

Device description. The ThermoCardiosystems (TCI) Heartmate LVAD was implanted in all patients. This device has a pusher-plate design with a stroke volume of 85 ml. The inflow to the device is attached to the left ventricular apex by

From the Divisions of Cardiothoracic Surgery and Circulatory Physiology, Columbia University College of Physicians and Surgeons, New York, New York.

Manuscript received April 2, 1997; revised manuscript received July 29, 1997, accepted August 21, 1997.

Address for correspondence: Dr. Joseph J. DeRose, Jr. c/o Dr. Mehmet Oz, Division of Cardiothoracic Surgery, Columbia University College of Physicians and Surgeons, Milstein Hospital Building, 177 Fort Washington Avenue, New York, New York 10032. E-mail: JJD11@columbia.edu.

Published by Elsevier Science Inc.

0735-1097/97/$17.00
PII S0735-1097(97)00396-3

JACC Vol. 30, No. 7
December 1997:1773–7

Abbreviations and Acronyms

LVAD = left ventricular assist device
RVAD = right ventricular assist device
TCI = ThermoCardiosystems
VE = vented electric

a Teflon sewing cuff, and a Dacron outflow graft is anastomosed to the lateral portion of the ascending aorta. The inflow and outflow conduits are guarded by 25-mm porcine valves that ensure unidirectional flow. The device is implanted in a properitoneal pocket in the left upper quadrant, and drivelines exit the abdominal wall in the left lower quadrant (Fig. 1). The interior, blood-contacting surface, is textured, promoting the rapid ingrowth of a biologic lining composed of platelets, endothelial-like cells, macrophages and lymphocytes (Fig. 2) (10). This biologic pseudointima makes anticoagulation unnecessary in the majority of cases (11). The device is normally operated in the automatic mode, which programs ejection when the device is 95% full.

The earlier designs of the TCI LVAD were powered by large pneumatic consoles that provided programmed pulses of air to the air chamber of the device, which resulted in displacement of the pusher plate upward and ejection of blood into the aorta. The pneumatic design allowed for patient ambulation and rehabilitation, but hospital discharge was not possible because of the bulky console. The vented electric (VE) design replaces the pneumatic chamber with an electrically powered low-speed torque motor. The motor drives a pair of cam-follower bearings, and as the rotor turns it displaces the pusher plate upward. The VE power supply and controller have been miniaturized, and a "wearable" system has been designed (Fig. 1). Power can be supplied by two batteries that can deliver up to 8 h of charge time and can be worn in two shoulder holsters. The controller fits in the palm of one hand and can be attached to a belt. The electrical driveline and a pneumatic vent line exit from the skin, which has allowed for unlimited patient ambulation with restriction only on activities that might submerge the vent line, such as swimming or bathing.

Figure 1. Schematic diagram of wearable VE LVAD. The device is powered by batteries worn on two shoulder holsters. The system controller fits in the palm of the hand and can be worn on a belt. A driveline containing the electric cables and a vent line exit the skin.

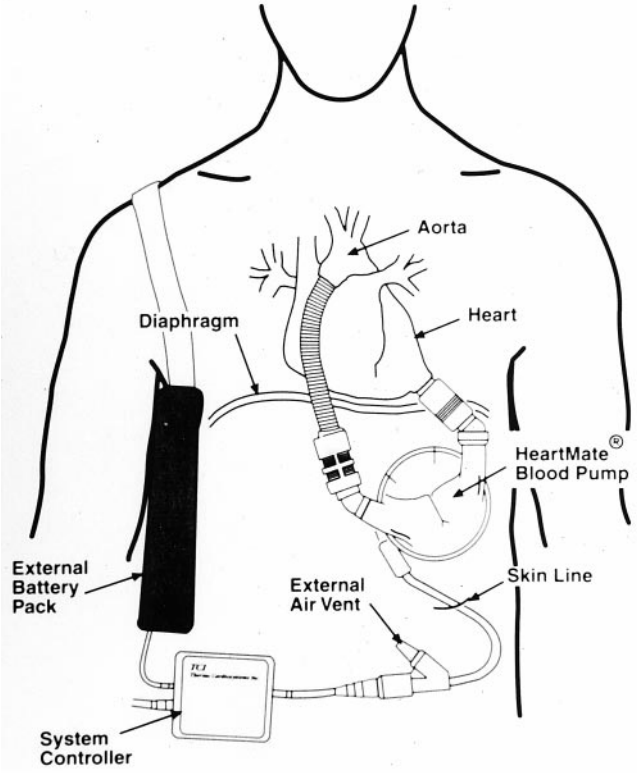

Figure 2. Photograph of the opened VE LVAD revealing the blood-contacting surfaces. The interior surfaces are textured, promoting the formation of a biologic neointima and making anticoagulation unnecessary in the majority of cases.

Three levels of fail safe rescue exist with the VE LVAD should device malfunction occur: 1) The native heart usually recovers enough function to keep the patient alive should no pump function exist. 2) The electronic control unit is extracorporeal and allows damaged software, chip or electronic failures to be easily fixed or replaced. 3) The pusher plate design allows hand-held pneumatic actuation should the electric motor of the device fail.

Selection criteria. Our criteria for LVAD implantation have been outlined elsewhere (3,12), and similar indications were used for implantation of the outpatient VE device. Briefly, hemodynamic evidence of cardiogenic shock, including a pulmonary capillary wedge pressure >20 mm Hg, and either a cardiac index <2.0 liters/min per m^2 or a systolic blood pressure <80 mm Hg despite maximal inotropic support were present in all patients. As with the earlier pneumatic experience, all eligible VE LVAD recipients were appropriate candidates for heart transplantation. Patients also had to have a body surface area >1.5 m^2 to accommodate the room necessary for properitoneal device insertion. Finally, potential VE recipients underwent a subjective assessment of their ability to

Table 1. Preoperative Characteristics of Patients Receiving In-Hospital Pneumatic or Outpatient Vented Electric Devices*

	Pneumatic (n = 52)	VE (n = 32)
Age (yr)	51 ± 2	49 ± 3
Range	13–65	11–65
Female	12 (23%)	6 (18%)
Indications for support		
Ischemic CM	28 (54%)	18 (56%)
Idiopathic dilated CM	19 (37%)	11 (35%)
Myocarditis	4 (7%)	0 (0%)
Hypertrophic CM	1 (2%)	2 (6%)
Adriamycin-induced CM	0 (0%)	1 (3%)

*p = NS for all comparisons. Data presented are mean value ± SEM, range or number (%) of patients. CM = cardiomyopathy; VE = vented electric.

care for and manage the device. A 24-h companion capable of operating and managing the device was likewise a prerequisite for VE LVAD insertion.

Patients. Between March 1993 and February 1997, 32 VE LVADs were implanted at our institution. The preoperative characteristics of the VE LVAD recipients (6 female, 26 male; mean [±SD] age 49 ± 3 years) are shown in Table 1 and are compared with the preoperative characteristics of our previous 52 pneumatic LVAD recipients. The youngest VE LVAD recipient was 11 years old and the oldest was 65. The major indications for VE LVAD insertion were ischemic cardiomyopathy (18 patients) and idiopathic dilated cardiomyopathy (11 patients). Of the patients with ischemic cardiomyopathy, three had placement of the device in the setting of postcardiotomy cardiogenic shock, and seven had incurred a myocardial infarction within 2 weeks of device placement.

Patient release protocol. With the institution of the VE LVAD recipient discharge program in 1993, several Food and Drug Administration (FDA) guidelines were established to ensure patient psychological and physical readiness to be away from medical personnel. These guidelines have been tailored to individual patient needs over the past 4 years as our experience with outpatient LVAD support has grown. In general, most patients undergo intensive inpatient rehabilitation and must be in functional class I before participating in the discharge protocol. Echocardiographic evidence should exist that the native heart can open the aortic valve when the LVAD is set at its lowest rate, to ensure that the patient can transiently maintain a blood pressure until manual pumping can commence should the device fail. Finally, both patient and a 24-h companion have to pass a training course on the use and care of the device, with particular attention to emergency interventions.

Once these general criteria are met, the patients undergo a gradual four-phase program of hospital discharge that begins with day trips lasting up to 16 h. On return to the hospital, both patient and companion fill out questionnaires to assess both compliance with device care and individual concerns and questions regarding medical and device management. Once several successful day trips are made, the patients are discharged for up to 3 days at a time. On return to the hospital, questionnaires again confirm compliance and identify potential problems. Once these extended periods away from the hospital are achieved successfully, the patients are fully discharged, with weekly follow-up in the LVAD outpatient clinic.

Table 2. Clinical Outcome of Patients Receiving Vented Electric Outpatient Device Versus In-Hospital Pneumatic Device*

	Pneumatic	VE
Duration of support (days)	100 ± 13	122 ± 26
Range	0–363	3–605
Transplantation	34 (65%)	20 (72%)
Explantation	2 (4%)	2 (7%)
Overall survival rate	69%	79%

*p = NS for all comparisons. Data presented are mean value ± SEM or number (%) of patients, unless otherwise indicated. VE = vented electric.

Statistics. Results are presented as the mean value ± SEM. Continuous variables were analyzed by the paired Student *t* test. The Fisher exact test for 2 × 2 tables was used for categoric variables. Analysis was considered significant at a p value ≤0.05.

Results

Clinical outcome. The clinical outcome of the 32 VE LVAD recipients is shown in Table 2 and is compared with that of the previous 52 pneumatic LVAD recipients. Of the 32 VE LVAD recipients, 20 have been bridged to transplantation, 1 has undergone explantation after 186 days of support, and 5 are currently on device support, for an overall survival rate of 77%. The VE LVAD recipients were supported for a mean of 122 ± 26 days, with the longest support times being 605, 541 and 412 days.

Of the 32 VE LVAD recipients, 4 underwent early heart transplantation and were therefore not able to participate in the discharge program. Of the remaining patients eligible for discharge, 3 took day trips only, 3 remain in hospital awaiting discharge, and 16 were fully discharged (Fig. 3). Most patients were transferred from the acute care cardiac service to the inpatient rehabilitation service within 30 days of implantation, with the earliest transfer occurring on postoperative day 7. The mean discharge day from the hospital was postoperative day 41 ± 4 (range 17 to 69). Among the 19 patients discharged to

Figure 3. Flowchart depicting the discharge disposition of 32 patients undergoing outpatient VE LVAD implantation. Three patients took day trips only, and 16 were fully discharged home.

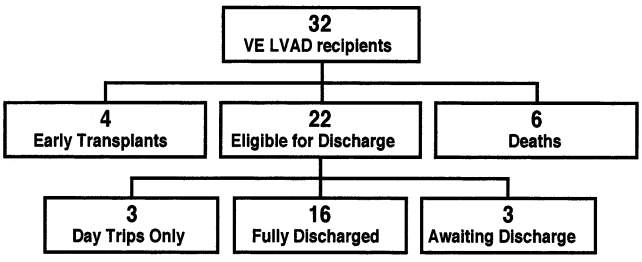

Table 3. Complications Among Patients Receiving Outpatient Vented Electric Devices and Inpatient Pneumatic Devices

	Pneumatic	VE	p Value
Intraoperative RVF	16 (30%)	8 (25%)	NS
Inotropic support	11	2	NS
NO	3	6	NS
RVAD	4	2	NS
Graft-related hemorrhage	4 (8%) 0.024 pt-mo support	4 (13%) 0.031 pt-mo support	0.06
Thromboembolism	3 (5.8%) 0.017/pt-mo support	2 (6%) 0.015/pt-mo support	NS
Device-related infection	18 (34%) 0.104 pt-mo support	9 (28%) 0.069 pt-mo support	NS

Data presented are number (%) of patients, unless otherwise indicated. RVF = right ventricular failure; NO = inhaled nitric oxide; pt = patient; RVAD = right ventricular assist device; VE = vented electric.

date, mean outpatient support has been 108 ± 30 days. The longest outpatient support times have been 466 days, 320 and 320 days. While discharged, patients have participated in a wide range of activities, including showering, tennis, bicycling, ballroom dancing and gardening. A majority of patients have also reported resuming normal sexual activity, and many have continued to work and attend school.

Complications. The complication rate among the VE LVAD recipients was similar to that encountered among the in-hospital pneumatic LVAD recipients (Table 3). *Perioperative right heart failure* was defined as an indexed LVAD output <1.8 liters/min per m^2 in the setting of elevated central venous pressure (>20 mm Hg) and a decompressed left ventricle and occurred in 6 patients (19%). Right heart failure was managed successfully with inhaled nitric oxide in four patients. Two patients required the combination of inhaled nitric oxide and temporary right ventricular assist device (RVAD) placement in the immediate postoperative period. RVAD support time was 4 and 13 days, respectively, and both patients survived to heart transplantation. Device-related infection occurred in eight patients (25%), for an incidence of 0.104/patient-month of support, and included device endocarditis in two patients, pocket infections in two and driveline infections in four. Suppression of infection was achieved with antibiotics and local wound care in five patients. Device infection necessitated explantation in one patient, and two patients required myocutaneous advancement flap procedures to contain local infections. There were four graft-related hemorrhages (13%) (0.024 events/patient-month of support), resulting in one death. Of the other three outflow graft holes, one occurred in the intensive care unit and was emergently repaired without neurologic sequelae. The other two were intermittent leaks that were diagnosed at weekly follow-up and repaired semiurgently without complication. The thromboembolism rate remained low at 6% (0.015 events/patient-months of support), and there were no embolic events in the outpatient setting. Of the two embolic phenomena, one occurred in a patient who had a large ventricular thrombus that was not appreciated by preoperative transesophageal echocardiography. The second cerebral embolism occurred in the setting of device endocarditis.

There were three device malfunctions that occurred after prolonged support. One patient had bearing wear in the setting of intermittent outflow graft obstruction, necessitating device replacement and graft revision on day 270 of support. A second patient had dislodgment of the pusher plate from the driver cam, requiring device replacement on day 296 of support. A third patient had malfunction of the cam position sensor in the setting of bearing wear. This patient was admitted, and the LE device was converted to a pneumatic console. He remained in the hospital for 3 months until uneventful heart transplantation.

Six deaths occurred due to intraoperative air embolism on day 3 of support, small bowel obstruction on day 11, intraoperative cerebral embolism on day 13, aortic tear on day 22, multisystem organ failure on day 40 and gastrointestinal hemorrhage on day 100, respectively. All deaths occurred in the hospital, none occurred in the outpatient setting.

Discussion

The inpatient bridge to transplantation experience has established the efficacy of circulatory assistance in normalizing hemodynamic status and restoring end-organ function (3–5). The ability to participate in aggressive rehabilitation has allowed patients to achieve higher functional class levels at the time of transplantation (6,7). Given that indications for implantation and patient selection were similar among VE LVAD and pneumatic LVAD recipients in our series, it is not surprising that identical benefits and survival statistics were enjoyed among in-hospital and outpatient LVAD recipients.

The complications encountered in the VE LVAD cohort were similar to those encountered in the pneumatic LVAD recipients. Most complications were not unique to outpatient LVAD support; rather, they were particular to mechanical support in critically ill patients. Once patients were well enough to be discharged from the hospital, few major complications occurred. After discharge, the most common reason for a patient to contact the LVAD team was controller malfunction or alarm signaling, which frequently prompted evening or emergent trips to the hospital, where interrogation of the system pinpointed the problem. Replacement or adjustment of the controller was usually sufficient, and patient lives were never in danger.

Our experience with >2,140 days of outpatient support with the VE LVAD has proved the reliability and safety of this therapy. Multiple advantages of such support over inhospital confinement exist. Both physical and psychological well-being are markedly improved among patients who are discharged from the hospital while awaiting transplantation. Among the 19 patients discharged from the hospital in this series, a number of them continued to work and attend school. Patients were able to shower and enjoy activities that included golf, tennis, bicycle riding, gardening, softball and ballroom dancing. Furthermore, almost all patients resumed sexual activity.

We recently (9) quantified this improvement in quality of life with rating scales, including the Nottingham health profile and the sickness impact profile. As early as 4 weeks after discharge, patients showed an improvement in most areas of quality of life examined. By 12 weeks after discharge, patients showed a statistically significant improvement in all aspects of quality of life. Similar findings have likewise been observed by Kendall et al. (13) among inhospital pneumatic LVAD recipients when preoperative quality of life measures were compared with postoperative scores. In the present study, it is not clear whether the major improvement in the sense of well-being is secondary to LVAD support or hospital discharge. However, of the in-hospital LVAD recipients studied by Kendall et al. (13), the aspect of pneumatic mechanical support that bothered patients most was confinement and tethering of the device. Finally, in this era of cost containment, outpatient LVAD support provides an alternative that is markedly less expensive than either inpatient mechanical support or long-term inpatient inotropic support (14).

Given the safety and efficacy of outpatient support as a bridge to transplantation, enthusiasm has grown for the use of mechanical circulatory devices as a destination therapy for end-stage heart disease. Debate still exists over whether wearable percutaneous systems or totally implantable systems will provide the best option for permanent mechanical circulatory support (15). The primary advantage of a percutaneous system is the location of the majority of device hardware outside the patient's body, which provides several layers of fail safe mechanisms should the device fail. However, that these devices are partially externalized also makes them extremely susceptible to eventual infection. Less rigid drivelines with antibiotic impregnation are currently being studied and may provide protection against inevitable infection. Totally implantable systems have the advantage of being completely contained within the patient and are therefore less susceptible to direct contamination. However, there are no fail safe mechanisms should device failure ensue.

Despite the use of angiotensin-converting enzyme inhibitors, the survival rate among subgroups of patients with functional class IV heart failure remains no higher than 25% at 2 years (16). Given these dismal statistics, a National Institutes of Health-sponsored, randomized trial (Randomized Evaluation of Mechanical Assistance for the Treatment of Congestive Heart Failure [REMATCH]) trial (8) has been established to compare destination VE LVAD support with medical therapy for patients with end-stage heart disease who are not considered candidates for transplantation.

Conclusions. Our short-term experience with the outpatient VE LVAD is encouraging and makes aggressive pursuance of the REMATCH trial imperative to assess whether current technology will provide a valuable long-term alternative to medical management for end-stage heart disease.

References

1. Funk D. Epidemiology of end-stage heart disease. In: Hogness JR, Van Antewerp M, editors. The Artificial Heart: Prototypes, Policies, and Patients: Committee to Evaluate the Artificial Heart Program of the National Heart, Lung, and Blood Institute. Washington, (D.C.): National Academy Press, 1991:251–61.
2. United Network for Organ Sharing (UNOS). Annual Report of the U.S. Scientific Registry for Organ Transplantation and the Organ Procurement and Transplantation Network. U.S. Washington (DC): Department of Health and Human Services, 1993.
3. Oz MC, Argenziano M, Catanese K, et al. Bridge experience with long term implantable left ventricular assist devices: are they an alternative to transplantation? Circulation 1997;95:1844–52.
4. Frazier OH, Rose EA, Macmanus Q, et al. Multicenter clinical evaluation of the HeartMate 1000 IP left ventricular assist device. Ann Thorac Surg 1992;53:1080–90.
5. McCarthy PM. Heartmate implantable left ventricular assist device: bridge to transplantation and future applications. Ann Thorac Surg 1995;59:Suppl: S46–51.
6. Frazier OH, Rose EA, McCarthy P, et al. Improved mortality and rehabilitation of transplant candidates treated with a long-term implantable left ventricular assist system. Ann Surg 1995;222:327–36.
7. Morrone TM, Buck LA, Catanese KA, et al. Early progressive mobilization of left ventricular assist device patients is safe and optimizes recovery prior to cardiac transplant. J Heart Lung Transplant 1996;15:423–9.
8. Rose EA, Goldstein DJ. Wearable long-term mechanical support for patients with end-stage heart disease: a tenable goal. Ann Thorac Surg 1996;61:399–402.
9. Catanese KA, Goldstein DJ, Williams DL, et al. Outpatient left ventricular assist device support: a destination rather than a bridge. Ann Thorac Surg 1996;62:646–53.
10. Spanier TB, Rose S, Schmidt AM, Itescu S. Interactions between dendritic cells and T cells on the surface of left ventricular assist devices leads to a TH2 pattern of cytokine production and B cell hyperreactivity in vivo [abstract]. Circulation 1996;94 Suppl I:I–293.
11. Slater JP, Rose EA, Levin HR, et al. Low thromboembolic risk without anticoagulation using advanced-design left ventricular assist devices. Ann Thorac Surg 1996;62:1321–8.
12. Oz MC, Goldstein DJ, Pepino P, Weinberg AD, et al. Selection scale predicts patients successfully receiving long-term, implantable left ventricular assist devices. Circulation 1995;92 Suppl II:II-169–73.
13. Kendall K, Sharp JW, McCarthy PM. Quality of life for hospitalized implantable LVAD patients. J Heart Lung Transplant 1994;13:S72–6.
14. Grewal RK, Gelijns AC, Rose EA, Oz MC. Clinical costs associated with LVAD implantation. J Heart Lung Transplant 1995;14:S89.
15. Pennington DG. Extended support with permanent systems: percutaneous versus totally implantable. Ann Thorac Surg 1996;61:403–6.
16. SOLVD Trial Investigators. Effect of enalapril on survival in patients with reduced ventricular ejection fractions and congestive heart failure. N Engl J Med 1991;325:293–302.