

Original Article

HeartSaver VAD: A Totally Implantable Ventricular Assist Device. Results of In Vivo Studies

Tofy Mussivand, PhD; Paul J. Henry, MD; Roy G. Masters, MD; Wilbert J. Keon, MD

Cardiovascular Devices Division, University of Ottawa Heart Institute, Ottawa, Ontario, Canada

Keywords: ventricular assist device, VAD, heart failure, HeartSaver VAD

Presented at the American Society of Extra-Corporal Technology 38th International Conference, April 13–16, 2000, Reno, Nevada

ABSTRACT

Currently, the most widely utilized ventricular assist devices (VADs) require percutaneous connections and are located either externally (e.g., Thoratec, Abiomed) or intra-abdominally (e.g., Novacor, TCI). These attributes have been implicated in a variety of complications (infection, thromboembolic, gastrointestinal, etc.). To address these concerns, a totally implantable VAD that requires no percutaneous connections and can be implanted in the left hemi-thorax has been developed.

The developed device has undergone in vivo evaluation as part of the design and development process. A total of 43 implants in the bovine model, with 5 device versions, have been conducted between July 1992 and February 2000. These studies successfully have demonstrated several important aspects of the developed device, including 1) feasibility of a totally implantable system; 2) capability of the device to support a dysfunctional heart; and 3) ability of the device to provide flows up to 10 L/min in a physiological setting.

The studies to date have played a vital role in the design and development process as well as demonstrating the feasibility of a totally implantable intrathoracic VAD. Based on these studies, design optimization was conducted, resulting in the development of the pre-clinical version of the device in preparation for clinical trials.

Address correspondence to:
Tofy Mussivand, PhD
Cardiovascular Devices Division
University of Ottawa Heart Institute
40 Ruskin St.
Ottawa, ON, Canada K1Y4W7
tofym@ottawaheart.ca

INTRODUCTION

Left ventricular assist devices (LVADs) have been demonstrated to be clinically effective for both short-term post-cardiotomy support as well as for longer-term support as a bridge to cardiac transplantation (1). Furthermore, the currently available devices have established evidence of improved functional and physiological condition in end-stage heart failure patients (2–5). This clinical experience has led to interest in the use of LVADs for longer-term use as a so-called “destination therapy.” Destination therapy would imply that the device was implanted with the intent of long-term or chronic support in terms of years as opposed to as a temporary bridge to transplantation or potential recovery. This approach would allow those patients who potentially could benefit from circulatory support but do not meet the current stringent guidelines for transplantation (which is currently a prerequisite for device implantation in the United States) access to this important technology.

Currently in North America and Europe, two major device types are widely available for clinical use: 1) console-based systems such as Thoratec Bi-VAD and Abiomed BVS-5000, which utilize externally placed pumps and are designed for in-hospital use and 2) wearable systems such as the Novacor Left Ventricular Assist Systems (LVAS) and Thermo Cardio-systems, Inc. (TCI) Heartmate, which utilize intra-abdominally implanted pumps and can be utilized outside of the hospital setting. Although both of these device types have specific merits for certain applications and some have been used quite successfully for extended durations of months and even years (6–8), neither can be considered truly ideal for use as a destination device, due to the issues explained below.

First, systems that utilize external pumps require the patient to be connected to a large and complex drive console, making their use outside of hospital for long periods of time unrealistic. The wearable systems, which do allow the potential for out-of-hospital use, are the more suitable choice from the existing devices for long-term use. However, these devices are not without their difficulties for use as a destination therapy. Perhaps the biggest challenge with the wearable systems is the complication rates experienced with these devices. Although a relatively high incidence of complications can be expected in the cohort of patients receiving these devices, the characteristics of these devices may also play an important role in the clinical complications experienced to date.

Infection is one of the major clinical complications associated with the use of circulatory support devices, with historical incidence rates of 25–45% (9). This high incidence rate has been attributed to the fact that these devices typically utilize percutaneous connections for venting, powering, and monitoring purposes. These percutaneous connections also reduce the quality of life of the device recipients, who must care for what is essentially an open wound on an ongoing basis. Furthermore, the impact of the high rate of ongoing infectious complications

may also play an important role in the thromboembolic complications, which also have substantial incidence rates (5–20%) in circulatory support patients (10). Currently available implantable devices also utilize an intra-abdominal implant site, which results in a somewhat lengthy cannulation to the natural heart, which may also play a major role in both the high rate of incidence of both infectious complications and thromboembolic complications. A further potential cause of infection is the size of the implanted devices such as the Novacor LVAS and TCI HeartMate, which are both over 1000 mL in volume.

Other difficulties with these systems include gastrointestinal complications, which have been experienced due to the intra-abdominal implantation site. In addition to these potential complications, the difficulty in implanting these systems may also play a role in the high level of complications experienced to date. The implantation of these devices requires extension of the standard median sternotomy to the umbilicus for device implantation, substantial surgical manipulation in the intra-abdominal area, and perforation of the recipient's diaphragm for cannulation to the natural heart.

To address these and other issues, the University of Ottawa Heart Institute (Ottawa, Canada) established the Canadian Artificial Heart Program in 1988, with the goal of developing a next generation LVAD designed specifically for long-term use outside of the hospital setting. The overall goal of the program was to develop a next-generation VAD, capable of being implanted in the thoracic cavity, that would require no percutaneous lines and would offer the patient the capability to leave the hospital and return to near-normal lifestyle activities with minimal limitations. The device (HeartSaver VAD) developed through this program has undergone *in vivo* evaluation as part of the development process as described herein.

MATERIALS AND METHODS

DEVICE DESCRIPTION

The HeartSaver VAD system as shown in Figure 1 is a pulsatile electro-hydraulically actuated VAD described previously (11–14). It utilizes implanted components (Figure 2), including the VAD unit, internal battery, and implanted energy and information transfer coil, as well as external components (Figure 3), including the remote biotelemetry monitor, external battery, and external energy, and information transfer coil.

The implantable VAD unit (Figure 4) combines the blood chamber, volume displacement chamber, electrohydraulic axial flow pump, and control electronics into a single unit with an overall volume of approximately 500 mL. The VAD unit is designed for implantation in the left hemithorax, and the geometry is based on cadaveric and intra-operative anatomical fit studies (15) as well as fluid dynamics optimization (16). The intrathoracic implant site allows for extremely short and direct cannulation in the human (Figure 4). Inflow cannulation is via the apex of the left ventricle and outflow is via the ascending aorta. In *in vivo* studies, the outflow cannulation is via the

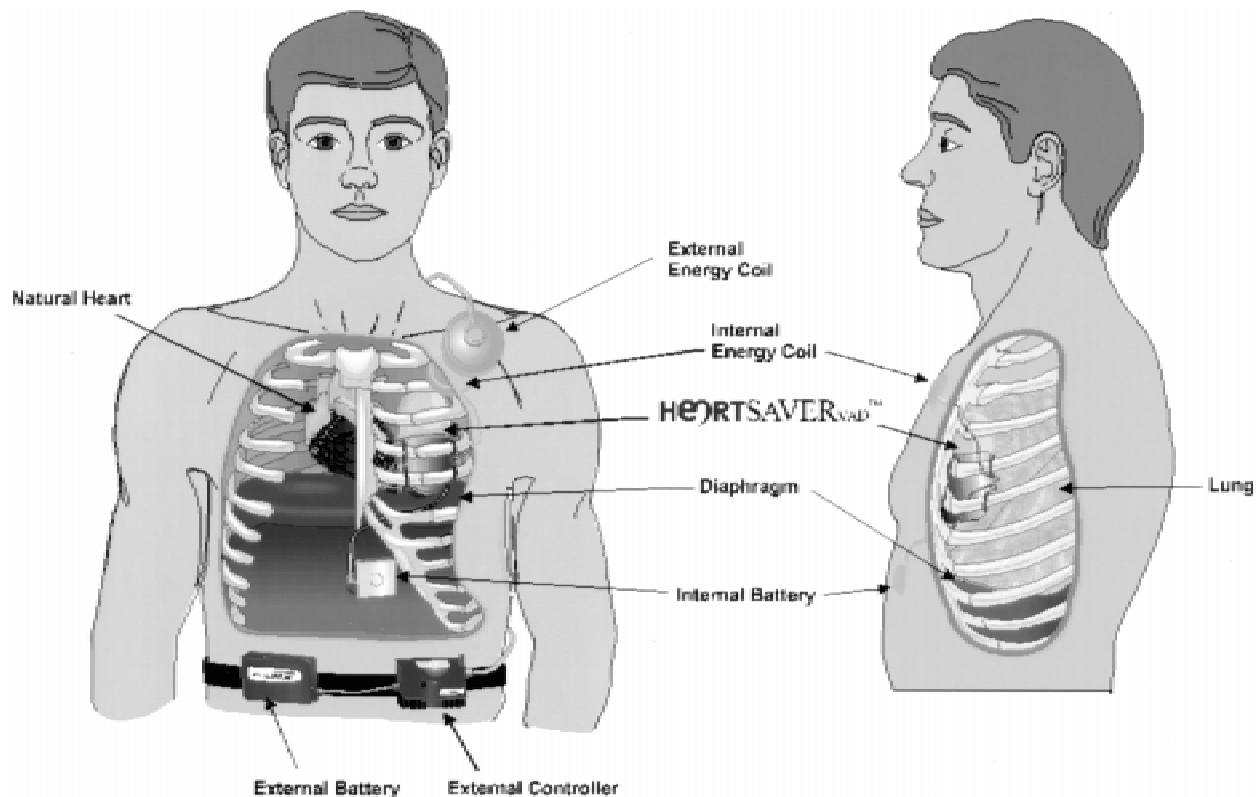


Figure 1: HeartSaver VAD system schematic.

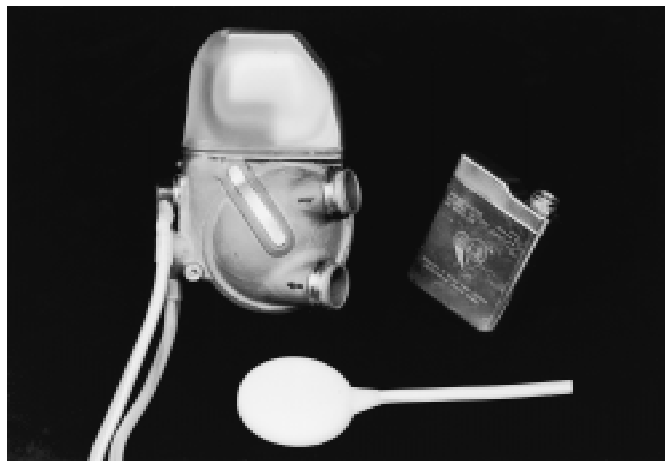


Figure 2: Implantable components: VAD unit, internal battery, and internal energy and information transfer coil.



Figure 3: Wearable components: external battery, biotelemetry monitor, and external energy and information transfer coil.

descending aorta due to differences in device placement in the calf model. An integrated volume displacement chamber adjacent to the lung allows the pressure of the system to equalize with atmospheric pressures, thus eliminating the requirement for external venting.

The unit is powered and monitored/controlled via the energy and information transfer coils, which allow transcutaneous transfer of energy and information through intact skin and tissue, thus eliminating the need for percutaneous connections

(17–21). The energy transfer system provides power to operate the VAD unit from a wearable external battery or other power source (automobile cigarette lighter, Household AC outlet, etc.). This system also charges the implanted battery, which allows the recipient the ability to bathe, shower, and partake in other activities without the need for any external power source. The information transfer system utilizes an infrared biotelemetry system integrated within the energy transfer coils.

A wearable remote biotelemetry monitor provides device

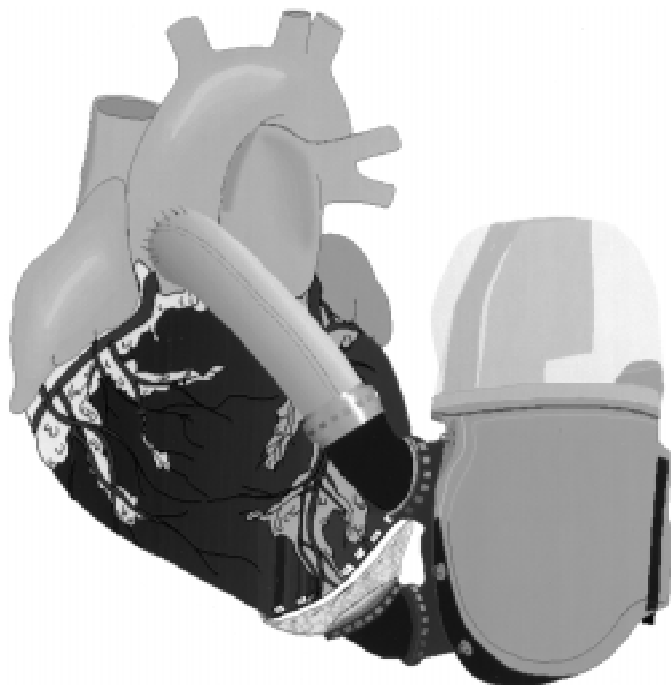


Figure 4: Clinical cannulation is inflow via the apex of the left ventricle and outflow to the ascending aorta (in the calf model outflow is to the descending aorta).

status displays and warning alarms via the infrared biotelemetry system. This monitor also offers the clinician the capability to perform routine device monitoring from a remote location, using phone lines or other public telecommunication infrastructure (i.e., satellite, Internet, ATM-asynchronous transfer mode systems, etc.), thus allowing patients the ability to leave the hospital and reduce the number of return visits for routine device assessment.

IN VIVO STUDIES

Three series of in vivo experiments have been conducted ($N = 43$) using various prototype versions of the device in male Holstein calves (22–25). The intent of all of the implants to date has been to supply input to the design process and to aid in the development of an appropriate implantation procedure.

The overall goal during the first series of implants ($N = 12$) was to obtain a successful implant of 5 days in order to prove the overall concept of the design. Once this goal was achieved, this series was terminated. After the various design inputs were used to revise the device design, a second series ($N = 13$) of implants was conducted. The goal for this series was to assess the design modifications, refine the implantation procedure, and achieve a successful 30-day implant. Once this goal was achieved, this series was also terminated, and design inputs were once again used to revise the device design, resulting in the final pre-clinical device form. To assess the pre-clinical device during the prototype manufacturing stage, a third series ($N = 18$) of implants was conducted. This series is ongoing in

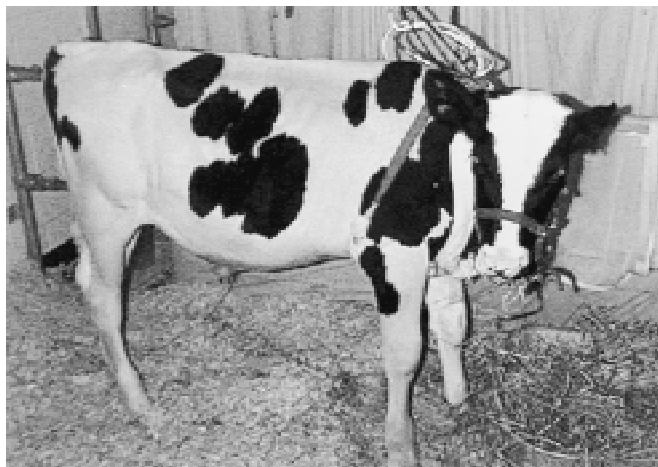


Figure 5: Calf with implanted HeartSaver VAD in the recovery area.

preparation for a formal multi-centre animal study to be used for regulatory purposes.

The implantation of the device after routine pre-operative screening and induction is implemented via a sixth intercostal space thoracotomy. After heparinization, cardiopulmonary bypass (CPB) is instituted in the left jugular vein and left carotid artery using a Biomedicus centrifugal pump.^a While CPB was utilized in the majority of cases, a series of six implants were conducted without the aid of CPB to assess the potential for non-bypass implantation of the device in the animal model. The pre-clotted outflow cannulae is anastomosed to the descending thoracic aorta utilizing a side-biting clamp, the pericardial sac is opened, and a pledgeted purse string suture is placed at the left ventricular apex for the apical inflow cannula. An apical ventriculotomy is performed using a 25-mm punch, and the apical tip of the inflow cannula is introduced into the left ventricle. The pledgeted sutures are then secured to the Dacron cuff of the apical inflow cannula. After device insertion and de-airing, the system is started in a fixed rate operating mode (default 50 BPM). Once functional operating status is confirmed by observation, and a stable hemodynamic condition is obtained, the device is switched to the Full/Fill–Full/Eject operating mode. After insertion of left and right chest tubes the chest incision is closed, and the animal is transferred into the recovery area. Figure 5 shows a calf implanted with the HeartSaver VAD in the recovery area. An automated data acquisition system is utilized to monitor and record the device and recipient parameters on an ongoing basis during the operative and post-operative phases.

RESULTS

During the first series of experiments ($N = 12$), the entire system, including the energy and information transfer sub-

^a Medtronic, Inc., Minneapolis, MN 55432

systems, was utilized to prove the overall concept of the design. During these experiments, the animals were supported for periods up to 5 days (Mean duration 16.5 hs, range 1.5 hs to 5 days). This series demonstrated the feasibility of a totally implanted system utilizing remote power transfer and wireless monitoring/control technologies and provided vital input for the device design and optimization process.

The second series of implants ($N = 13$) were conducted with a modified version of the device and focussed on performance of the implanted VAD unit, specifically the inflow and outflow cannulae, the blood chamber fluid dynamics, and device positioning in the calf model. In this series of experiments, the animals were supported for periods up to 30 days (mean duration 3.5 days, range 1 h to 30 days). This series successfully demonstrated the ability of the device to support a dysfunctional heart (ventricular fibrillation), allowed assessment of device modifications implemented as a result of the series 1 implants, and provided further input into the device design and optimization efforts.

The third series of implants ($N = 18$) is currently ongoing and is designed to assess the pre-clinical version of the device in preparation for a formal multi-centre animal trial. This series has concentrated on optimizing the implant procedure and assessing implantability/ease of use of individual components in their pre-clinical form, as they become available from the pilot manufacturing facility. For these reasons, most of the third series of implants have been acute implants lasting no more than 1 day (typically a couple of hours).

Preparations for the formal animal trial are currently underway. This trial is a prospective, multi-centre trial based on the guidelines (26) established by the National Institute of Health, Food and Drug Administration, Society of Thoracic Surgeons, and the American Society for Artificial Internal Organs. The trial will focus on achieving eight long-term (90 day) survivors and will assess hemodynamics at 30 and 90 days, monitor continuous device performance, and track all adverse events (including hemolysis, infection, thrombo-embolism, and end-organ damage). The results of this study will be used for regulatory purposes to obtain approval to begin clinical utilization of the HeartSaver VAD.

DISCUSSION

As the field of circulatory supports moves forward towards more widespread utilization and into longer-term use as a destination therapy, the importance of quality of life for the device recipients could not be more important. While the devices need to be technically sound and have lower complication rates, they must also address the needs of the recipient to maintain a near normal lifestyle. This concept has been an overriding goal of the HeartSaver VAD development and has been the focus in our goal of a totally implantable system. With a totally implantable system, patients should be able to resume near-

normal life activities. For example, while operating with the internal battery, the patient will be able to remove all the external components, allowing them to participate in the widest possible variety of activities, such as swimming and bathing. Other efforts towards improving the patients quality of life include the implementation of the remote monitoring and control capability, which will allow the patient and device to be monitored remotely, thus reducing or eliminating the need for the patient to return to the hospital for routine device assessments.

Finally, we hope that once this device enters the clinical arena, that not only will the device have a reduced level of clinical complications, due to the specific device characteristics (i.e., totally implantable, intrathoracic location, etc.), but that the device recipients will be provided with an enhanced quality of life due to these characteristics.

ACKNOWLEDGMENTS

This work was supported in part by the University of Ottawa Heart Institute, Industry Canada, and the World Heart Corporation (Ottawa, Ontario, Canada).

REFERENCES

1. Goldstein DJ, Oz MC, Rose EA. Implantable left ventricular assist devices. *N Engl J Med.* 1998;339:1522–33.
2. 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.
3. Levin HR, Chen JM, Oz MC, et al. Potential of left ventricular assist devices as outpatient therapy while awaiting transplantation. *Ann Thorac Surg.* 1994;58:1515–20.
4. Kormos RL, Murali S, Dew MA, et al. Chronic mechanical circulatory support: rehabilitation, low morbidity, and superior survival. *Ann Thorac Surg.* 1994;57:51–8.
5. Miller PJ, Billich TJ, LaForge DH, et al. Initial clinical experience with a wearable controller for the Novacor left ventricular assist system. *ASAIO J.* 1994;40:M465–70.
6. 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.
7. Myers TJ, Catanese KA, Vargo RL, Dresslers DK. Extended cardiac support with a portable left ventricular assist system in the home. *ASAIO J.* 1996;42:M576–9.
8. Oz MC, Argenziano M, Catanese KA, et al. Bridge experience with long-term implantable left ventricular assist devices: Are they an alternative to transplantation? *Circulation.* 1997;95:1844–52.
9. Argenziano M, Oz MC, Rose EA. The continuing evolution of mechanical ventricular assistance. *Curr Probl Surg.* 1997;34:328–86.

10. Didisheim P, Olsen DB, Farrar DJ, et al. Infections and thromboembolism with implantable cardiovascular devices. *Trans Am Soc Artif Intern Organs*. 1989;35:54–70.
11. Mussivand T, Hendry PJ, Masters RG, Holmes KS, Hum A, Keon WJ. A remotely controlled and powered artificial heart pump. *Artif Organs*. 1996;20:1314–9.
12. Mussivand TV, Hendry PJ, Masters RG, Keon WJ. Multipurpose mechanical circulatory device. *Int J Artif Organs*. 1997;20:217–21.
13. Mussivand TV, Hendry PJ, Masters RG, Keon WJ. Evaluation of a totally implantable intrathoracic ventricular assist device. *Cor Europaeum* 1997;6:110–14.
14. Mussivand T, Hendry PJ, Masters RG, Keon WJ. Development of a totally implantable intrathoracic ventricular assist device. In: Akutsu T, Koyangi H, eds. *Heart Replacement—Artificial Heart 6*. Tokyo: Springer-Verlag; 1998;15–20.
15. Mussivand T, Masters RG, Hendry PJ, et al. Critical anatomic dimensions for intrathoracic circulatory assist devices. *Artif Organs*, 1992;16:281–5.
16. Mussivand T, Day KD, Naber BD. Fluid dynamic optimization of a ventricular assist device using particle image velocimetry. *ASAIO J*. 1999;45:25–31.
17. Mussivand T, Miller JA, Santerre PJ, et al. Transcutaneous energy transfer system performance evaluation. *Artif Organs*. 1993;17:940–7.
18. Mussivand T, Hum A, Holmes KS. Remote energy transmission for powering artificial hearts and assist devices. In: Akutsu T, Koyangi H, eds. *Heart Replacement—Artificial Heart 6*. Tokyo: Springer-Verlag, 1998;344–7.
19. Mussivand T, Hum A, Diguer M, et al. A transcutaneous energy and information transfer system for implanted medical devices. *ASAIO J*. 1995;41:M253–8.
20. Mussivand T, Hum A, Holmes KS, Hendry PJ, Masters RG, Keon WJ. Remote monitoring & control of artificial hearts and assist devices. In: Akutsu T, Koyangi H, eds. *Heart Replacement—Artificial Heart 6*. Tokyo: Springer-Verlag, 1998;370–3.
21. Mussivand T, Hum A, Holmes KS, Keon WJ. Wireless monitoring & control for implantable rotary blood pumps. *Artif Organs*. 1997;21:661–4.
22. Hendry P, Masters RG, Ibrahim M, et al. In vivo evaluation of an intrathoracic ventricular assist device. *ASAIO J*. 1999;45:123–6.
23. Hendry PJ, Master RG, Keaney M, Bourke M, Mussivand T, Keon WJ and The EVAD Team. Evolution of an electrohydraulic ventricular assist device through in vivo testing. *ASAIO J*. 1996;42:M350–4.
24. Mussivand T, Hendry PJ, Masters RG, Keon WJ. Evaluation of a totally implantable intrathoracic ventricular assist device. *Cor Europaeum*. 1997;6:110–14.
25. Mussivand T, Masters RG, Hendry PJ, Keon WJ. Totally implantable intrathoracic ventricular assist device. *Ann Thorac Surg*. 1996;61:444–7.
26. Pantalos GM, Altieri F, Berson A, et al. Long-term mechanical circulatory support system reliability recommendation: American Society for Artificial Internal Organs and The Society of Thoracic Surgeons: long-term mechanical circulatory support system reliability recommendation. *Ann Thorac Surg*. 1998;66:1852–9.