Mechanical Circulatory Assistance – An Evolving Therapy –

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Although heart transplantation is the gold standard for the treatment of advanced stage heart failure, the implantation of mechanical circulatory support devices (MCSDs) has become a well-established therapy for this disease. As the population of patients with severe heart failure has grown, the utilization of MCSDs has increased considerably. That trend is expected to continue, especially in light of dramatic advances in MCSD technology. This review outlines the current status and future directions of mechanical circulatory support therapy in the setting of a constantly evolving field of supportive devices and adjuvant therapies. (*Circ J* 2011; **75**: 38–46)

Key Words: Congestive heart failure; Heart transplantation; INTERMACS; Mechanical circulatory support; Ventricular assist device

Congestive heart failure (CHF) has become a leading cause of morbidity and mortality in developed countries. As medical, electrical and surgical therapy for CHF has been refined, the population of patients living with end-stage CHF has expanded dramatically.¹ While cardiac transplantation has evolved as a life-saving therapy for selected patients, its applicability is limited by a shortage of donor organs.² Mechanical circulatory support devices (MCSDs) have therefore been developed to augment or supplant cardiac function in patients with intractable heart failure. These devices are now increasingly and successfully employed as a bridge to transplantation (BTT), a bridge to recovery (BTR), or as long-term therapy for end-stage heart failure (permanent “destination” therapy or “bridge to decision (BTD)” therapy).³ This trend is expected to continue, especially in light of the 1 October 2003 decision of the Centers for Medicare and Medicaid Services (CMS) to provide reimbursement for MCSD implantation surgery.

During the last 2 decades, there has been significant technical progress in the development of MCSDs. So-called “first-generation” devices consisting of pulsatile, positive displacements pumps were introduced into clinical practice in the 1990s.⁴ “Second-generation” axial flow rotary pumps with contact bearings were introduced from 1998 to 2000.⁴ Currently, “third-generation” MCSDs, which consist of suspended rotary pumps without contact bearings, are undergoing clinical investigation. Throughout this period of engineering and technological innovation, there has also been significant evolution in the clinical management of MCSD recipients. The purpose of this review is to assess and delineate the current status of mechanical circulatory support therapy for intractable CHF in the setting of a constantly evolving field of supportive devices and adjunctive therapies.

Utilization Strategies

The original goal in MCSD development was to employ them for the purpose of long-term circulatory support; however, clinical use of devices has evolved into a number of specific strategies for device use. MCSDs were initially implanted for a limited duration in order to support transplant candidates who otherwise might not survive until a suitable donor heart became available. This designation has been termed “BTT” and is still the most common initial MCSD utilization strategy in 2010 (43.7% of reported implants in the USA since March

Table 1. Major Adverse Events After Mechanical Circulatory Support Device Implantation

Arterial non-central nervous system thromboembolism
Bleeding
Cardiac arrhythmia
Device malfunction
Hemolysis
Hepatic dysfunction
Hypertension
Major infection
Myocardial infarction
Neurological dysfunction
Pericardial collection
Psychiatric episode
Renal dysfunction
Respiratory failure
Right heart failure
Venous thrombosis
Wound dehiscence

Received October 26, 2010; accepted October 27, 2010; released online December 7, 2010

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ISSN-1346-9843 doi:10.1253/circj.CJ-10-1091

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Table 2. INTERMACS Patient Profiles and Current Utilization of MCS D Therapy

INTERMACS profile	Profile description	Timing of intervention	N	%
Profile 1	Critical cardiogenic shock	Within hours	792	27.0
Profile 2	Progressive decline despite inotropic support	Within days	1,215	41.4
Profile 3	Stable but inotrope dependent	Within weeks to a few months	461	15.7
Profile 4	Resting symptoms	Within weeks to a few months	281	9.5
Profile 5	Exertion intolerant	Variable, depends upon nutrition, organ function and activity	69	2.3
Profile 6	Exertion limited	Variable, depends upon nutrition, organ function and activity	62	2.1
Profile 7	Advanced NYHA III	MCS D therapy may not currently be indicated	53	1.8
Total			2,933	100.0

INTERMACS, Interagency Registry for Mechanically Assisted Circulatory Support; MCS D, Mechanical Circulatory Support Device.
Data derived from INTERMACS Quarterly report July 2010.

2006).⁵ Additionally, the BTT designation has been further delineated to include patients not actively listed for transplant but who may become eligible following initiation of MCS D therapy. This designation has been termed “BTD”. The BTD designation is now defined by the Interagency Registry for Mechanically Assisted Circulatory Support (INTERMACS) as: (1) Possible BTT—likely to be eligible, (2) Possible BTT—moderate likelihood of becoming eligible and (3) Possible BTT—unlikely to become eligible. Currently, INTERMACS reports that the possible BTT designation accounts for an additional 41.2% of reported US MCS D implants since March 2006.⁵ Less frequently, MCS Ds are utilized to support the failing heart temporarily until it recovers (“BTR”) sufficiently for MCS to be discontinued (2.1% of reported US MCS D implants since March 2006).⁵ Finally, nearly 20 years after the first devices were implanted as BTT, the FDA approved the HeartMate XVE (Thoratec, Pleasanton, CA, USA) for permanent therapy (“destination therapy (DT)”) in patients not considered transplant candidates. Growing in utilization for a multitude of reasons, DT currently accounts for 11.6% of US MCS D implants.⁵ While designation of a specific strategy is required in the USA for reimbursement purposes, the clinical applicability of a specific strategy may not be clear at the time of implantation and may be dynamic, as patients may migrate from one strategy to another.⁶

MCS D Data Analysis

In 1991, the Institute of Medicine recognized the need for detailed longitudinal data on patients receiving mechanical circulatory support.⁷ However, collection of rigorous scientific data has lagged behind device development.⁴ The International Society for Heart and Lung Transplantation (ISHLT) MCS D Database was therefore developed and implemented in 2001 to collect data from institutions around the world. In June 2006, INTERMACS, funded through a 5-year contract from the US National Institutes of Health (NIH), assumed responsibility for collecting device data from centers in the USA. The ISHLT is currently developing an international MCS registry devoted to the collection of device data from institutions worldwide. Additionally, the US CMS now “requires submission to a national audited registry of health data on all VAD DT patients from the date of implantation throughout the remainder of their lives”. This requires inclusion of all devices designed for chronic implantation regardless of initial intent. This requirement has therefore facilitated both accrual of MCS D recipients into INTERMACS and the

number of centers participating in the registry.

It is important to note that INTERMACS data is collected only on FDA-approved MCS Ds and therefore does not include devices under FDA investigation. Given the number of devices currently under FDA investigation and the broad population of patients who can potentially benefit from MCS D therapy, it is certain that reported INTERMACS data significantly under represents the current number of MCS D implants in the USA.

In the first year of INTERMACS, 395 MCS D implants were reported. MCS D implants increased in the 3 subsequent years to 442, 984 and 1112, respectively.⁵ Additionally, the number of participating centers in the USA increased from less than 40 in June 2006 to 113 as of 19 July 2010.⁵ The rapid expansion of MCS D utilization is further highlighted as follows. From the inception of INTERMACS prospective data collection in June 2006 until April 2008, monthly device implantations ranged from 19 to 50 (mean=31). By contrast, from May 2008 until June 2010, device implantations ranged from 61 to 137 (mean=84). This dramatic growth in MCS D use mirrors the FDA approval of the HeartMate II (Thoratec) for BTT in April 2008. A similar upstroke in MCS D implantation occurred when the HeartMate II received FDA approval for DT in January 2010. Given the expanding population of patients surviving with CHF, it is expected that MCS D implantations will continue to expand as additional devices receive FDA approval.

INTERMACS data has also led to the generation of 7 clinical profiles to stratify acuity and severity of CHF to assess the need for MCS D therapy as well as the risk associated with MCS D implantation.^{8–10} Table 2 details the 7 patient profiles and the current INTERMACS data regarding utilization of MCS Ds in these populations.^{5,10}

First-Generation MCS Ds

The term “first-generation” refers to pulsatile, positive displacement pumps that were the initial MCS Ds introduced into clinical practice. Of these, the prototypical devices are the Novacor left ventricular assist system (LVAS, WorldHeart, Salt Lake City, UT, USA), the HeartMate XVE and the Thoratec IVAD (implantable ventricular assist device). The Thoratec PVAD (paracorporeal ventricular assist device) deserves mention as another commonly utilized pulsatile-flow MCS D, in which the blood pump lies external to the patient and is therefore appropriate for temporary use for the BTT and BTR indications. This device is perhaps the most utilized device

Figure 1. HeartMate XVE (Thoratec, Pleasanton, CA, USA) just prior to implantation.

in the history of mechanical circulatory support. The Toyobo LVAS (Toyobo Co Ltd, Osaka, Japan) is also a paracorporeal pneumatic pulsatile device, and is noteworthy in that it is the only device approved for use in Japan, which has an extreme shortage of donor hearts available for transplantation for social and ethical reasons.^{11,12} This situation in Japan has forced both prolonged use of the Toyobo LVAS, which was initially designed for short-term use, and has led to the adoption of more aggressive criteria for MCS D weaning in that country.^{13,14}

The Novacor LVAS was first implanted in a human in 1984 and was used successfully as BTT in that patient. It

gained CE mark approval in Europe in 1994 without restriction as to the indication for use, and subsequently received FDA approval for use as BTT in 1998. The HeartMate XVE device (variably referred to as the TCI IP, TCI VE and HeartMate I during its lifetime due to the acquisition of ThermoCardiosystems Inc by Thoratec) received FDA approval for BTT in 2001 and DT in 2003, and also holds CE mark approval. It holds the distinction as the only long-term implantable MCS D not requiring systemic anticoagulation therapy (see [Figure 1](#)). The Thoratec IVAD, FDA-approved for BTT and BTR, is the only implantable MCS D approved for biventricular support. Due to the large size of first-generation devices, their applicability to patients with smaller body surface area is limited. Additionally, due to the complexity of the pump function with multiple moving mechanical parts, device durability is limited. Therefore, first-generation devices have largely been supplanted by newer devices.

Second-Generation MCS Ds

Second-generation MCS Ds were the first to utilize continuous rather than pulsatile blood flow. This design creates the advantage of smaller size, allowing use in smaller patients who could not have received first-generation devices. Additionally, blood flow is generated by an axial rotor, which minimizes the number of moving parts to the rotor itself and the support bearings, thereby increasing durability. Second-generation MCS Ds include the Jarvik 2000 (Jarvik Heart, New York, NY, USA), the MicroMed DeBakey VAD (MicroMed Technologies, Woodlands, TX, USA) and the Heartmate II. The Jarvik 2000 generates continuous axial flow via a rotor supported by ceramic bearings and is currently under FDA investigation in the USA as BTT therapy. It has CE mark certification in Europe for BTT, BTR and DT. The DeBakey VAD generates continuous axial flow via a similar mechanism and is undergoing clinical trials in the USA for the BTT indication. The pediatric version (HeartAssist 5) is the only pediatric MCS D approved for use in the USA and is also approved for use in Europe. The HeartMate II generates continuous axial flow via a rotor supported by ball and cup bearings (see [Figure 2](#)). It is the only second-generation MCS D

Figure 2. HeartMate II (Thoratec, Pleasanton, CA, USA) just prior to implantation.

that has FDA approval for BTT and DT. As noted above, its FDA approval (for BTT in April 2008 and DT in January 2010) has dramatically increased the number of MCSd implants in the USA.

Third-Generation MCSds

Like second-generation MCSds, third-generation devices utilize continuous flow generated either by a centrifugal or axial rotor. However, the impeller or rotor is suspended in the MCSd by using either hydrodynamic or electromagnetic forces, thus removing the need for support bearings and reducing the number of moving parts to one. This technology increases the mechanical durability of the device while also generally decreasing device size. Some devices are even small enough to be positioned above the diaphragm or entirely within the pericardial space.

Currently, 4 such devices are undergoing clinical investigation in the USA, including the Berlin Heart Incor (Berlin Heart, Berlin, Germany), the Levacor VAD (WorldHeart), the HeartWare HVAD (see [Figure 3](#)) (HeartWare International, Inc, Framingham, MA, USA) and the DuraHeart (Terumo

Heart Inc, Ann Arbor, MI, USA). Of these, the Berlin Heart Incor, the HeartWare HVAD and the Terumo DuraHeart are CE mark approved for use in Europe. The DuraHeart (see [Figure 4](#)) is notable as the first third-generation device to enter clinical trials, which began in Europe in 2004.¹⁵ It was subsequently the first third-generation MCSd to gain CE mark approval in Europe, showing favorable outcomes compared with pulsatile devices, and leading the market revolution towards increased utilization of third-generation devices.¹⁶ The HeartWare HVAD has the advantage that its smaller size allows it to be positioned entirely within the pericardial space, thereby decreasing the invasiveness of the implant operation and associated surgical morbidity. The Levacor VAD is depicted in [Figure 5](#).

Technical Aspects of MCSd Implantation

The vast majority of devices are implanted via a median sternotomy. Usually, prior to systemic heparinization for cardiopulmonary bypass, the appropriate pump pocket is created either in the abdomen, the pre-peritoneal space, or the subcutaneous space. The patient is then systemically heparinized

and aortic and right atrial cannulation are performed. These cannulas are positioned in locations to optimize available territory for subsequent cannulation for transplantation. For example, the aortic cannula should be placed just inside the pericardial reflection and the IVC and SVC are left alone. A de-airing catheter is also placed in the ascending aorta just proximal to the aortic cannula. This venting cannula is run at 500 cc/min throughout the operation to ensure de-airing of the ascending aorta. The patient is initiated on bypass and the heart is positioned to expose the apex. Every effort is made to avoid aortic cross clamping, thereby protecting the right ventricle. The left ventricular (LV) apex is cored and the LV apical cannula is sutured into position. The LVAD is placed into the left ventricle and the heart is repositioned. The entire system is de-aired. The outflow graft is then looped around the right atrium within the pericardium, cut to an appropriate length and bevel, and then anastomosed to the ascending aorta using a side-biting clamp. The position of this graft should be low enough to provide sufficient ascending aorta for subsequent transplantation; however, not so low as to present extreme difficulty with the use of the side-biter or interfere with the right atrium or the right main coronary artery. The

side-biter is removed and replaced on the graft just adjacent to the anastomosis. The LVAD is then de-aired through the clamped graft via a needle hole in the graft. The graft is then unclamped and the entire system is de-aired extensively with TEE guidance. The patient is then weaned from cardiopulmonary bypass and transitioned over to LVAD. During this time, the anesthesiologist is optimizing the right ventricular function with proper alteration of the pre-load and pulmonary vascular afterload. The pre-load can be altered significantly with volume addition and removal, as well as with increased atrial pacing rate. Systemic inotropes are added and an inhaled pulmonary vasodilator can be added to further reduce the pulmonary vascular resistance. The ventilator should be optimized to hyperoxygenate and reduce the pCO₂ to further decrease pulmonary vascular resistance. The patient is then decannulated and anticoagulation is reversed with protamine. Hemostasis is obtained. Thoracostomy tubes are very carefully placed to keep in mind avoiding compression of the aortic outflow graft as well as traversing the drive line, which was brought out via separate stab incision in the abdominal skin. Every effort is made to route the aortic outflow away from the midline to avoid injury during mediastinal re-entry. Pericardial fat and the pericardium should be layered over the heart and VAD cannulas as much as possible to further reduce the risk of injury during mediastinal re-entry.

Adverse Events

During the development of INTERMACS, surgeons, cardiologists, industry professionals and the FDA pioneered precise definitions of 17 MCS-related adverse events (see [Table 1](#)). Of these, critical device-related adverse events that deserve mention include device malfunction or failure, neurological events, infection and right heart failure. One of the major factors limiting the long-term use of MCSs has been mechanical device malfunctions or failures. First-generation devices are particularly susceptible to such malfunctions due to the greater complexity of their mechanical functions.¹⁷ The simpler designs utilized in second- and third-generation devices have thus far shown improved mechanical durability and are expected to ultimately have little bearing on device therapy as the technology advances.¹⁸ Adverse neurological events continue to be a significant source of morbidity in MCS recipients. One key drawback of continuous flow devices is increased thrombogenicity, mandating anticoagulation. Nonetheless, the incidence of neurological adverse events in a study of the HeartMate II, the most frequently utilized second-generation MCS in the USA, compared favorably to previously published data for pulsatile pumps.^{18,19}

Infection continues to be a survival-limiting factor for MCS recipients. Specifically, the rate of percutaneous driveline infection is the primary infectious factor limiting long-term patient survival.^{20,21} Pulsatile first-generation devices require volume compensation via a connection to either an external pneumatic drive console or an atmospheric vent, and this component of their design is integrated into the percutaneous lead along with the wires for transmission of electrical power. Second- and third-generation devices do not require external venting due to the mechanics of flow-generation, and therefore generally have smaller percutaneous leads than first-generation devices. This feature of continuous-flow MCSs is expected to decrease the rate of driveline infection; however, this remains to be seen and it is certain that driveline infections will not be entirely eliminated with the new devices.

Right heart failure is an additional adverse event asso-

Figure 6. The total artificial heart (SynCardia Systems, Inc, Tuscon, AZ, USA). (A) Device components prior to implantation. (B) Implanted TAH in vivo.

ciated with MCS therapy and is addressed in the following section.

Biventricular Failure and Support

Development of right ventricular (RV) failure after LV assist device implantation has received considerable attention recently because it significantly increases perioperative morbidity and mortality.^{22,23} Multiple intraoperative tactics can be utilized to minimize the risk of postoperative RV failure. These include rapid atrial pacing, inhaled pulmonary vasodilators, inotropes, ventilator optimization and prevention of myocardial ischemia by avoiding the use of an aortic cross-clamp. Currently there are no universal selection criteria for the institution of univentricular vs. biventricular support. The present literature identifies at least 25 different predictors of post-LVAD RV dysfunction, yet few have been supported by multiple investigators.^{24–32} Therefore, we developed a risk scoring system based on the following 5 criteria derived from analysis of 266 LVAD insertions at our institution: cardiac index $\leq 2.2 \text{ L} \cdot \text{min}^{-1} \cdot \text{m}^{-2}$ (odds ratio 5.7), RV stroke work index $\leq 0.25 \text{ mmHg} \cdot \text{L}^{-1} \cdot \text{m}^{-2}$ (odds ratio 5.1), serum creatinine $\geq 1.9 \text{ mg/dl}$ (odds ratio 4.8), previous cardiac surgery (odds ratio 4.5) and systolic blood pressure $\leq 96 \text{ mmHg}$ (odds ratio 2.9).³³ Based on these 5 clinical predictors, we constructed an algorithm that predicts the risk of RVAD in patients requiring LVAD therapy with $>80\%$ sensitivity and specificity. Further-

more, we investigated in the same patient cohort the effect on clinical outcome when RVAD implantation was planned early based on the presence of risk factors for RV failure.³⁴ Early RVAD insertion was associated with significantly improved survival to hospital discharge (51% vs. 29%, $P < 0.05$). This was further confirmed in Kaplan-Meier survival analysis both at 1 year and long-term. Therefore, we have shown that patients at high risk for post-LVAD RV failure can be identified prior to the initiation of MCS therapy, and the survival of this cohort can be improved by the early institution of biventricular mechanical support. Of course, the up-front knowledge that a patient requires biventricular mechanical circulatory support influences the type of device(s) selected for MCS therapy and the implant strategy. Specifically, patients who require biventricular support must be considered potential transplant candidates as no device(s) are approved for biventricular DT. The total artificial heart (SynCardia Systems, Inc, Tuscon, AZ, USA) is an emerging option for such patients, although there are only 31 centers worldwide currently approved for implantation of this device (see Figure 6).³⁵

Future Development

One of the key engineering challenges in the development of implantable pneumatically driven pulsatile blood pumps was volume compensation. As the diaphragm-type blood pumps eject blood, an equivalent volume of air or fluid must enter

Figure 7. Radiographs demonstrating the relative size of first-, second- and third-generation devices. (A) HeartMate XVE; (B) HeartMate II; (C) HeartWare HVAD.

Figure 8. Synergy Pocket Micro-Pump (CircuLite, Inc, Saddle Brook, NJ, USA). (A) Blood pump; (B) 3-dimensional CT scan reconstruction of pump, cannulae and percutaneous lead after implantation.

the nonblood side of the pump housing to prevent a vacuum from forming. Without this volume compensation, the amount of energy consumed increases fourfold, making the energy requirement impractical.³⁶ Because of difficulty in resolving problems with implantable compliance chambers for volume compensation, the early pulsatile pumps were designed with external pneumatic drives or an atmospheric vent. Because the skin was being penetrated for volume compensation, it was most efficient to transmit electrical energy through percutaneous wires included with the venting apparatus. One of the key advantages to rotary continuous flow second- and third-generation devices is that they do not require volume compensation. However, second- and third-generation MCSDs are still utilizing percutaneous energy transmission. To minimize the risk of device-related infection, the ideal long-term MCSD would be totally implantable (ie, no component of the device penetrates the skin). This goal is achievable with the use of a transcutaneous energy transmission system (TETS).

TETS operation is based on the inductive coupling of energy between an external primary coil and an internal secondary coil placed subcutaneously. The primary coil is positioned on the surface of the skin over the secondary coil, and electrical energy is transmitted between the coils. TETSs have been developed and utilized successfully in both an LVAD (LionHeart 2000 LVAD, Arrow International, Reading, PA, USA) and a total artificial heart (AbioCor TAH, Abiomed, Danvers, MA, USA), although for reasons unrelated to the TETS, neither of these devices is currently in use.³⁶ Manufacturers of MCSDs are currently developing TETS technology and the availability of a totally implantable MCSD is likely in the near future.

Future development of MCSD technology is based on the likelihood that the population of patients requiring circulatory support for CHF will continue to expand. This mandates continued development of durable devices designed for long-term use and will be dependent on establishing safety of MCSDs and the safety of the implant operation. As safety and reliability improve, it is natural to expect that MCSDs will be implanted earlier in the course of CHF. With this population of patients, it will be particularly important to minimize the morbidity of the implant operation with the development of percutaneous, minimally invasive and off-pump surgical approaches for implantation of MCSDs (see **Figure 7**). Devices designed for partial circulatory support will also play a significant role in the management of patients with less severe profiles of heart failure. One such device is the Synergy Pocket Micro-Pump (CircuLite, Inc, Saddle Brook, NJ, USA), which is designed to provide up to 3 L/min of blood flow for partial circulatory support, is implanted without the need for cardiopulmonary bypass or median sternotomy and has a blood pump approximately the size of a AA battery (see **Figure 8**). It is currently undergoing clinical investigation with favorable initial results.³⁷

Summary

MCS D therapy has become a well-established therapy for intractable CHF. Technological advances have increased the safety and efficacy of MCS D therapy with the use of smaller, more durable devices designed for long-term circulatory support. The need for long-term support is expected to increase as the availability of donor hearts for transplantation remains relatively fixed and the population of patients with advanced CHF continues to expand. Further development of MCS D technology has the potential to revolutionize the management

of chronic heart failure with the use of minimally invasive surgical approaches for the placement of totally implantable devices, utilized in patients with less severe profiles of CHF.

References

- Lloyd-Jones D, Adams RJ, Brown TM, Carnethon M, Dai S, De Simone G, et al. Heart disease and stroke statistics--2010 update: A report from the American Heart Association. *Circulation* 2010; **121**: e46–e215.
- Komoda T, Drews T, Hetzer R, Lehmkuhl HB. New prioritization of heart transplant candidates on mechanical circulatory support in an era of severe donor shortage. *J Heart Lung Transplant* 2010; **29**: 989–996.
- Johnson MR, Meyer KH, Haft J, Kinder D, Webber SA, Dyke DB. Heart transplantation in the United States, 1999–2008. *Am J Transplant* 2010; **10**: 1035–1046.
- Kirklin JK, Naftel DC. Mechanical circulatory support: Registering a therapy in evolution. *Circ Heart Fail* 2008; **1**: 200–205.
- Kirklin JK, Naftel DC, Myers SL, Clark ML, Collum C. INTERMACS Quarterly Statistical Report: 1 March 2006–30 June 2010. <http://www.intermacs.org> (accessed 25 October, 2010).
- Jessup M, Stevenson LW, Desvigne-Nickens P, Young J, Acker MA, Milano C, et al. Patient with mechanical circulatory support: Is implant strategy static or dynamic? *J Heart Lung Transplant* 2008; **27**(2S): S61.
- Institute of Medicine. The artificial heart: Prototypes, policies, and patients. Washington, DC: The National Academies Press, 1991.
- Kirklin JK, Naftel DC, Stevenson LW, Kormos RL, Pagani FD, Miller MA, et al. INTERMACS database for durable devices for circulatory support: First annual report. *J Heart Lung Transplant* 2008; **27**: 1065–1072.
- Kirklin JK, Naftel DC, Kormos RL, Stevenson RL, Pagani FD, Miller MA, et al. Second INTERMACS annual report: More than 1,000 primary left ventricular assist device implants. *J Heart Lung Transplant* 2010; **29**: 1–10.
- Stevenson LW, Pagani FD, Young JB, Jessup M, Miller L, Kormos RL, et al. INTERMACS profiles of advanced heart failure: The current picture. *J Heart Lung Transplant* 2009; **28**: 535–541.
- Saito S, Nishinaka T, Yamazaki K. Long-term support with a left ventricular assist device therapy in Japan. *Circ J* 2010; **74**: 624–625.
- Saito S, Matsumiya G, Sakaguchi T, Fujita T, Kuratani T, Ichikawa H, et al. Fifteen-year experience with Toyobo paracorporeal left ventricular assist system. *J Artif Organs* 2009; **12**: 27–34.
- Saito S, Matsumiya G, Sakaguchi T, Miyagawa S, Yoshikawa Y, Yamauchi T, et al. Risk factor analysis of long-term support with left ventricular assist system. *Circ J* 2010; **74**: 715–722.
- Matsumiya G, Saitoh S, Sakata Y, Sawa Y. Myocardial recovery by mechanical unloading with left ventricular assist system. *Circ J* 2009; **73**: 1386–1392.
- Nishinaka T, Schima H, Roethy W, Rajek A, Nojiri C, Wlner E, et al. The DuraHeart VAD, a magnetically levitated centrifugal pump: The University of Vienna bridge-to-transplant experience. *Circ J* 2006; **70**: 1421–1425.
- Morshuis M, Schoenbrodt M, Nojiri C, Roefe D, Schulte-Eistrup S, Boergemann J, et al. DuraHeart magnetically levitated centrifugal left ventricular assist system for advanced heart failure patients. *Expert Rev Med Devices* 2010; **7**: 173–183.
- Omoto R, Kyo S, Nishimura M, Matsuda H, Matsumiya G, Kitamura S, et al. Japanese multicenter clinical evaluation of the HeartMate vented electric left ventricular assist system. *J Artif Organs* 2005; **8**: 34–40.
- Miller LW, Pagani FD, Russell SD, John R, Boyle AJ, Aaronson KD, et al. Use of a continuous-flow device in patients awaiting heart transplantation. *N Engl J Med* 2007; **357**: 885–896.
- Frazier OH, Rose EA, Oz MC, Dembitsky W, McCarthy P, Radovancevic B, et al. Multicenter clinical evaluation of the HeartMate vented electric left ventricular assist system in patients awaiting heart transplantation. *J Thorac Cardiovasc Surg* 2001; **122**: 1186–1195.
- John R, Pagani FD, Naka Y, Boyle A, Conte JV, Russell SD, et al. Post-cardiac transplant survival after support with a continuous-flow left ventricular assist device: Impact of duration of left ventricular assist device support and other variables. *J Thorac Cardiovasc Surg* 2010; **140**: 174–181.
- Holman WL, Kirklin JK, Naftel DC, Kormos RL, Desvigne-Nickens P, Camacho MT, et al. Infection after implantation of pulsatile mechanical circulatory support devices. *J Thorac Cardiovasc*

- Surg* 2010; **139**: 1632–1636.
22. Wilson ST, Mudge GH, Stewart GC, Givertz MM. Evaluation for a left ventricular assist device: Selecting the appropriate candidate. *Circulation* 2009; **119**: 2225–2232.
23. Kormos RL, Teuteberg JJ, Pagani FD, Russell SD, John R, Miller LW, et al. Right ventricular failure in patients with the HeartMate II continuous-flow left ventricular assist device: Incidence, risk factors, and effect on outcomes. *J Thorac Cardiovasc Surg* 2010; **139**: 1316–1324.
24. Dang NC, Topkara VK, Mercado M, Kay J, Kruger KH, Aboodi MS, et al. Right heart failure after left ventricular assist device implantation in patients with chronic congestive heart failure. *J Heart Lung Transplant* 2006; **25**: 1–6.
25. Morgan JA, John R, Lee BJ, Oz MC, Naka Y. Is severe right ventricular failure in left ventricular assist device recipients a risk factor for unsuccessful bridging to transplant and post-transplant mortality. *Ann Thorac Surg* 2004; **77**: 859–863.
26. Kavarana MN, Pessin-Minsley MS, Urtecho J, Catanese KA, Flannery M, Oz MC, et al. Right ventricular dysfunction and organ failure in left ventricular assist device recipients: A continuing problem. *Ann Thorac Surg* 2002; **73**: 745–750.
27. Kormos RL, Gasior TA, Kawai A, Pham SM, Murali S, Hattler BG, et al. Transplant candidate's clinical status rather than right ventricular function defines need for univentricular versus biventricular support. *J Thorac Cardiovasc Surg* 1996; **111**: 773–783.
28. Tsukui H, Teuteberg JJ, Murali S, McNamara DM, Buchanan JR, Winowich S, et al. Biventricular assist device utilization for patients with morbid congestive heart failure: A justifiable strategy. *Circulation* 2005; **112**(Suppl I): I-65–I-72.
29. Santambrogio L, Bianchi T, Fuardo M, Gazzoli F, Veronesi R, Braschi A, et al. Right ventricular failure after left ventricular assist device insertion: Preoperative risk factors. *Interact CardioVasc Thorac Surg* 2006; **5**: 379–382.
30. Ochiai Y, McCarthy PM, Smedira NG, Banbury MK, Navia JL, Feng J, et al. Predictors of severe right ventricular failure after implantable left ventricular assist device insertion: Analysis of 245 patients. *Circulation* 2002; **106**: I-198–I-202.
31. Fukamachi K, McCarthy PM, Smedira NG, Vargo RL, Starling RC, Young JB. Preoperative risk factors for right ventricular failure after implantable left ventricular assist device insertion. *Ann Thorac Surg* 1999; **68**: 2181–2184.
32. Farrar DJ, Hill JD, Pennington DG, McBride LR, Holman WL, Kormos RL, et al. Preoperative and postoperative comparison of patients with univentricular and biventricular support with the thoratec ventricular assist device as a bridge to cardiac transplantation. *J Thorac Cardiovasc Surg* 1997; **113**: 202–209.
33. Fitzpatrick JR, Frederick JR, Hsu VM, Kozin ED, O'Hara ML, Howell E, et al. Risk score derived from preoperative data analysis predicts the need for biventricular mechanical circulatory support. *J Heart Lung Transplant* 2008; **27**: 1286–1292.
34. Fitzpatrick JR, Frederick JR, Hiesinger W, Hsu VM, McCormick RC, Kozin ED, et al. Early planned institution of biventricular mechanical circulatory support results in improved outcomes compared with delayed conversion of a left ventricular assist device to a biventricular assist device. *J Thorac Cardiovasc Surg* 2009; **137**: 971–977.
35. Yoda M, El-Banayosy A, Tenderich G, Koerfer R, Minami K. The CardioWest total artificial heart for chronic heart transplant rejection. *Circ J* 2009; **73**: 1167–1168.
36. Slaughter MS, Myers TJ. Transcutaneous energy transmission for mechanical circulatory support systems: History, current status, and future prospects. *J Card Surg* 2010; **25**: 484–489.
37. Klotz S, Meyns B, Simon A, Wittwer T, Rahmanian P, Schlensak C, et al. Partial mechanical long-term support with the CircuLite Synergy pump as bridge-to-transplant in congestive heart failure. *Thorac Cardiovasc Surg* 2010; **58**(S2): 173–178.