Bridging to transplant with the HeartMate left ventricular assist device: The Columbia Presbyterian 12-year experience

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Objective: Implantation of a left ventricular assist device as a bridge to transplantation has become an acceptable approach for patients with end-stage heart failure. Our long-term results with 3 Thoratec HeartMate devices are presented to outline improvements in successful bridging to transplantation and post-transplant survival.

Methods: From August 1990 through January 2003, 243 patients underwent implantation of Thoratec HeartMate devices as a bridge to transplantation. This included 52 (21.4%) pneumatic devices, 17 (7.0%) dual-lead vented electric devices, and 174 (71.6%) single-lead vented electric devices.

Results: Mean age was 49.7 ± 13.7 years. Mean support time was 78.1 ± 82.9 days (0-541). Bridging success increased from 63.5% (n = 33) for pneumatic devices to 64.7% (n = 11) for dual-lead vented electric devices and 72.4% (n = 126) for single-lead vented electric devices ($P = .005$). Posttransplant 1-, 3-, and 5-year actuarial survival increased from 87.5%, 78.1%, and 71.9% in patients with pneumatic devices to 91.5%, 86.9%, and 81.3%, respectively, for patients with single-lead vented electric devices. Device infection and malfunction occurred in 17.7% (n = 43) and 12.8% (n = 31) of patients, respectively.

Conclusions: Successful bridging to transplantation and posttransplant survival has improved over time. Left ventricular assist devices have become increasingly more effective in bridging patients with end-stage heart failure to transplantation. This is likely due to a combination of better patient selection, improvements in clinical practice, and evolution in device design.

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Cardiac failure remains the leading cause of death in the United States, affecting more than 5 million individuals with approximately 400,000 new cases diagnosed each year.^{1,2} Implantation of a left ventricular assist device (LVAD) as a bridge to transplantation has become an acceptable approach for patients with end-stage heart failure.³⁻⁶ Potential complications, however, include bleeding, right heart failure, stroke, device-related infections, and device malfunction.^{7,8}

Over the last 12 years, the HeartMate (Themocardiosystems, Woburn, Mass) has been the preferred device at our institution for bridging patients with end-stage heart failure to transplantation and has been used with the greatest frequency.⁹⁻¹² With

this device, patients can be stabilized and discharged from the hospital to wait for their heart transplant at home.¹³⁻¹⁵

Early survival data of patients undergoing LVAD insertion revealed greater than 30% hospital mortality. Since the initiation of our LVAD program in 1990, there have been many clinical improvements in perioperative care.⁹ We reviewed our 12-year experience with 3 different HeartMate devices, focusing on the temporal changes in duration of support, bridge to transplant success, and posttransplant survival. Additionally, we evaluated the incidence of the most common device-related complications, including infection, device malfunction, and stroke, as well as causes of death for those patients who expired on LVAD support. Finally, we outlined preoperative, intraoperative, and postoperative improvements in care as well as advancements in device design that have favorably impacted the success of LVADs in bridging patients to transplantation.

We challenged ourselves to answer the following questions: Has bridging success to transplantation improved over the years as device design and clinical practices have evolved? What were the primary advancements in preoperative, intraoperative, and postoperative care that may have been responsible for improved bridging to transplant success? Finally, was our recently reported LVAD screening scale accurate in its ability to predict survival to transplant?

Patients and Methods

From August 1990 through January 2003, 243 patients underwent implantation of a Thoratec HeartMate device. This included 52 (21.4%) pneumatic (PNEUM), 17 (7.0%) dual-lead vented electric (DLVE), and 174 (71.6%) single-lead vented electric (SLVE) devices. Data were collected prospectively and analyzed retrospectively. Initial approval for device placement was obtained from the institutional review board and informed consent was obtained from each patient.

Duration of support, bridging to transplant success, survival posttransplant, incidence of infection, and device malfunction were evaluated based on type of device and time period. Infection was defined as the presence of a positive culture along with a leukocytosis. Device malfunction was categorized into electrical, mechanical, and technical causes.

We previously reported a preoperative scoring system that predicts successful bridging to transplant.¹⁶ LVAD implantation scores, derived from 5 clinical variables, including ventilatory dependence, postcardiotomy shock, previous LVAD, central venous pressure >16 mm Hg, and prothrombin time >16 seconds, were calculated for patients with SLVE devices.¹⁶ LVAD scores were classified as low (0-4), medium (5-7), and high (8-10), with an inverse relationship between score and clinical stability. Mean LVAD score during each year was calculated and all years were compared.

Statistical Analysis

Data were represented as frequency distributions and simple percentages. Values of continuous variables were expressed as a mean $\pm$ standard deviation (SD). Continuous variables were compared using analysis of variance (ANOVA-Bonferroni), whereas cate-

gorical variables were compared by means of chi-square tests. Kaplan-Meier analysis was used to calculate long-term survival along with a log-rank *P* value when comparing groups. Actuarial survival was calculated by constructing life tables. Significant predictors of bridging to transplant success were investigated by examining the association between various preoperative variables and bridging success in univariate analysis, followed by a stepwise logistic regression analysis on factors demonstrated to be significant in univariate analysis. Variables included age, sex, race, etiology of heart failure, development of infection, device malfunction, and LVAD implantation scores. All data were analyzed utilizing SPSS 11.5 (SPSS Inc, Chicago, Ill).

Results

Demographics

Table 1 outlines the clinical characteristics of LVAD recipients. Mean overall age was 49.7 ± 13.7 years, with 197 (81.1%) men and 46 (18.9%) women. Coronary artery disease (CAD) was the most common etiology of heart failure, present in 138 (56.8%) patients. Idiopathic cardiomyopathy (ICM) was the second most common etiology, identified in 87 (35.8%) patients. Other etiologies occurred in 18 (7.4%) patients and included postpartum cardiomyopathy (CM) (*n* = 2, 0.8%), hypertrophic CM (*n* = 4, 1.6%), amyloidosis (*n* = 3, 1.2%), and myocarditis (*n* = 9, 3.7%).

Overall mechanical support time was 78.1 ± 82.9 (0-541) days. Mean support time significantly decreased from a mean of 99.0 ± 91.8 days for PNEUM devices to 65.3 ± 66.2 days for SLVE devices (*P* < .001).

Bridging to Transplant Success

Bridging to transplant success significantly increased from 63.5% (*n* = 33) for PNEUM devices to 72.4% (*n* = 126) for SLVE devices (*P* = .005; Figure 1). Causes of death for patients who expired on LVAD support are listed in Table 2.

Posttransplant Survival

Overall actuarial survival at 1, 3, 5, and 10 years posttransplant was 90.5%, 85.1%, 69.6%, and 39.6%, respectively (Figure 2). Posttransplant 1-, 3-, and 5-year actuarial survival increased from 87.5%, 78.1%, and 71.9% for PNEUM devices to 91.5%, 86.9%, and 81.3%, respectively, for SLVE devices. Posttransplant survival was similar for patients who were bridged to transplant with an LVAD as compared to nonbridged patients operated on during the same time period at our institution (*P* = NS; Figure 2).

Explantation of Devices

Over the 12-year study period, 10 devices were explanted. This included 2 PNEUM devices, 3 DLVE devices, and 5 SLVE devices. Seven of 10 devices were explanted because of infection, whereas 3 were explanted because of left ventricular recovery in patients with myocarditis, idiopathic cardiomyopathy, and acute myocardial infarction with ventricular rupture (all patients with SLVE devices).

TABLE 1. Clinical characteristics of LVAD recipients

	PNEUM	DLVE	SLVE	P	Overall
Mean age (years)	51.1 ± 11.2*	49.5 ± 16.2	49.2 ± 14.1	.665	49.7 ± 13.7
Gender					
Male	40 (76.9%)†	15 (88.2%)	142 (81.6%)	.549	197 (81.1%)
Female	12 (23.1%)	2 (11.8%)	32 (18.4%)		46 (18.9%)
Race					
Caucasian	42 (80.8%)	15 (88.2%)	129 (74.1%)	.317	186 (76.5%)
African American	8 (15.4%)	1 (5.9%)	30 (17.2%)	.265	39 (16.0%)
Other	2 (3.8%)	1 (5.9%)	15 (8.6%)	.592	18 (7.4%)
Etiology of heart failure					
CAD	29 (55.8%)	11 (64.7%)	98 (56.3%)	.672	138 (56.8%)
ICM	18 (34.6%)	5 (29.4%)	64 (36.8%)	.635	87 (35.8%)
Other	5 (9.6%)	1 (5.9%)	12 (6.9%)	.935	18 (7.4%)
Duration of support (days)	99.0 ± 91.8	136.9 ± 145.6	65.3 ± 66.2	<.001	78.1 ± 82.9
Range (days)	0–362	11–541	0–397		0–541
Infection					
Drive line	6 (11.5%)	0 (0.0%)	12 (6.9%)	.299	18 (7.4%)
Pocket	1 (1.9%)	0 (0.0%)	14 (8.0%)	.029	15 (6.2%)
Pump	6 (11.5%)	0 (0.0%)	4 (2.3%)	.008	10 (4.1%)
Any	13 (25.0%)	0 (0.0%)	30 (17.2%)	.036	43 (17.7%)

LVAD, Left ventricular assist device; PNEUM, pneumatic device; DLVE, dual-lead vented electric device; SLVE, single-lead vented electric device; CAD, coronary artery disease; ICM, idiopathic cardiomyopathy.

*Mean ± Standard deviation.

†Absolute number (percentage of total).

Infection and Device Malfunction

The overall incidence of infection was 17.7% (n = 43), occurring in 25.0% (n = 13) of patients with PNEUM devices, 0.0% (n = 0) of patients with DLVE devices, and 17.2% (n = 30) of patients with SLVE devices (Table 1). Device malfunctions occurred in 15.4% (n = 8) of PNEUM devices, 29.4% (n = 5) of DLVE devices, and 10.3% (n = 18) of SLVE devices (Table 3). When considering only those device malfunctions that were clinically significant (excluding incidental findings at explantation), the incidence was 11.5% (n = 6) in PNEUM devices, 23.5% (n = 4) in DLVE devices, and 5.7% (n = 10) in SLVE devices (Table 3).

Neurological Complications While on LVAD Support

The incidence of postoperative cerebrovascular accident (CVA) and transient ischemic attack (TIA) is outlined in Table 4. Postoperative stroke (within 30 days of LVAD implantation) occurred in 7.7% (n = 4) of patients with PNEUM devices, 11.8% (n = 2) of patients with DLVE devices, and 4.0% (n = 7) of patients with SLVE devices (P = .443).

Severe Right Ventricular Failure While on LVAD Support

The incidence of severe right ventricular failure requiring placement of a right ventricular assist device (RVAD) occurred in 5 (29.4%) patients with DLVE devices and 12

(6.9%) patients with SLVE devices. Bridging to transplant was successful in 11 (64.7%) of these patients supported by an RVAD.

LVAD Score

LVAD implantation scores increased from 2.6 ± 3.1 in 1996, to 3.8 ± 3.3 in 1997, to 4.9 ± 3.6 in 1998, to 5.3 ± 3.5 in 1999, and to 5.4 ± 3.8 in 2000. Scores then decreased to 5.3 ± 3.3 in 2001 and 4.7 ± 3.4 in 2002 (P = .297).

Predictors of Survival

Univariate analysis. Table 5 outlines numerous variables that were evaluated for their impact on bridging to transplant success using univariate analysis. Significant risk factors adversely affecting survival included female gender (P = .001), etiology of heart failure (CAD: P = .044; ICM: P = .003; other: P = .048), duration of LVAD support (P < .001), and LVAD score (P < .001). Additionally, there was a trend toward significance for advanced age (P = .080) and pocket infections (P = .095).

Multivariate analysis. Only LVAD score (odds ratio 1.214, 95% confidence interval 1.119–1.316, P < .001, standard error 0.041) was a significant predictor of survival to transplant using multivariate, stepwise logistic regression analysis (Table 6). Bridging to transplant was successful in 88.6% of low-scoring patients, 64.5% of medium-scoring patients, and 48.9% of high-scoring patients (P < .001; Figure 3).

Figure 1. Outcome after insertion of LVAD. Bridging to transplant success increased from 63.5% (n = 33) for patients with PNEUM devices, to 64.7% (n = 11) for patients with DLVE devices, and 72.4% (n = 126) for patients with SLVE devices.

Discussion

LVADs continue to serve as an effective bridge to transplantation for patients with end-stage heart failure. Of the 243 patients who underwent implantation of HeartMate devices as a bridge to transplantation at our institution over the last 12 years, 170 (70.0%) were successfully transplanted. We are encouraged by our results that demonstrate a progressive improvement in both bridging to transplant success and posttransplant survival.

Improvements in bridge to transplant success and post-transplant survival occurred along with concomitant temporal changes in device designs. We believe the reasons for improvement in these outcome variables are multifactorial and cannot be attributed to changes in device design alone. Over the last 12 years, there have been numerous improvements in patient selection, surgical techniques, treatments for right ventricular (RV) dysfunction, establishment of intraoperative hemostasis, and pre- and postoperative intensive care unit care. As it would be nearly impossible to quantify the exact contribution of each of these individual advancements to the progressive improvement in outcome over the last 12 years, we would like to highlight several of the preoperative, intraoperative, and postoperative factors that we believe have most significantly impacted outcome in patients undergoing implantation of an LVAD as a bridge to transplant (Table 7).

Improvements in patient selection and medical optimization prior to LVAD implantation have been the primary preoperative factors that have contributed to improved outcome. LVAD implantation score was the only statistically significant predictor of bridging to transplant success. This confirmed our belief that patients who are sicker at the time

TABLE 2. Causes of deaths for patients who died on LVAD support

Cause of death	PNEUM	DLVE	SLVE	P*
MSOF	3	0	13	.378
Sepsis	6	0	8	.267
CVA	2	2	7	.665
Bleeding	3	0	3	.323
Device malfunction	2	1	4	.544

LVAD, Left ventricular assist device; PNEUM, pneumatic device; DLVE, dual-lead vented electric device; SLVE, single-lead vented electric device; MSOF, multisystem organ failure; CVA, cerebrovascular accident.

*P values from chi-square analysis.

of LVAD implantation (high LVAD score) exhibit increased mortality during the period of mechanical assistance and decreased likelihood of being successfully bridged to transplantation.

Optimizing fluid balance by promoting diuresis with the use of diuretics and early institution of continuous venovenous hemofiltration (CVVH), as well as enhancing renal perfusion with the use of an intra-aortic balloon pump, can optimize RV function. Although we currently lack objective, intrainstitutional data, we believe that optimizing a patient's preoperative fluid status decreases the incidence of postoperative RV dysfunction.

Improvements in intraoperative clinical practices have centered around 3 areas: RV function after LVAD implantation, decreased bleeding as a result of refined surgical techniques, and the use of aprotinin, as well as prophylaxis against infections with topical antibiotic placed around the peritoneal LVAD pocket.

LVAD support induces a variety of hemodynamic changes with resulting effects on RV function.^{17,18} RV failure refractory to maximal pharmacological therapy occurs in 20% to 40% of patients supported with an LVAD.^{17,18} Though the use of inotropes and vasodilators may be successful, their effectiveness is limited because they concomitantly increase the incidence of cardiac arrhythmias, systemic hypotension, and derangement of alveolar gas exchange. Early in our experience, we performed a randomized, double-blind trial of inhaled nitric oxide (NO) in LVAD recipients with pulmonary hypertension.¹⁹ Patients randomized to receive inhaled NO demonstrated a significant reduction in pulmonary vascular resistance (PVR), along with increased LVAD output.¹⁹ Patients receiving placebo did not show a significant response but demonstrated impressive hemodynamic improvement when crossed over to the inhaled NO group.¹⁹ Prior to the widespread availability of inhaled NO at our institution, 4 of 19 LVAD recipients with RV failure required RVAD support with an associated mortality of 50%.¹⁸ However, more recently, in an analysis of 69 LVAD recipients, although the incidence of RV failure was 30%, RV mechanical support

Figure 2. Posttransplant survival for patients bridged to transplant with a LVAD versus nonbridged patients operated on during the same time period at our institution. There was no significant difference in posttransplant survival, with median survival of 8.2 years for LVAD patients and 8.6 years for non-LVAD patients ($P = .563$).

was required in only 1 patient.¹⁸ Though this study did not focus on the use of NO, more than half the recipients received NO perioperatively. More than 65% of patients who received NO avoided the need for an RVAD. This indicates that the use of NO may have contributed to the decreased incidence of RV failure. It is important to note that concomitant preoperative measures to reduce volume overload (such as CVVH), avoidance of excessive transfusions, and administration of phosphodiesterase inhibitors are also important in preventing and treating RV failure. Despite overall improvements in the management of RV failure, the ability to consistently predict the development of RV failure in LVAD recipients is still lacking. This knowledge will be of greater importance as the use of LVADs for destination therapy increases.

In our early experience, bleeding was a major limiting factor in the successful use of an LVAD as a bridge to transplant. Intraoperative and postoperative requirements for extensive blood product usage leads to a cytokine-mediated increase in PVR, with resulting adverse effects on RV function. We performed a retrospective multicenter analysis that demonstrated aprotinin to be associated with a significant decrease in postoperative blood loss and transfusion requirements.²⁰ Additionally, aprotinin recipients demonstrated an approximate 50% reduction in postoperative requirement for an RVAD, as well as a significant reduction in mortality.²⁰ We have since used aprotinin routinely in all patients undergoing LVAD implantation.

Refinements in the operative technique for LVAD implantation have also reduced the degree of postoperative

bleeding. One of the most common sites for bleeding to occur is at the anastomosis between the left ventricle outflow tract and the aorta. In 2001, we modified our surgical technique for implanting LVADs to evert the suture line to provide enhanced tissue approximation, as previously described.²¹ BioGlue (Cryolife, Kennesaw, Ga) is then generously applied over the aortic outflow graft anastomosis.²¹

Another improvement in intraoperative practice has been the prophylactic use of vancomycin paste around the peritoneal pocket during LVAD implantation.²² Since incorporating this into our practice a few years ago, we have noticed a decreased incidence of pocket infections (within SLVE patients).²²

Treatment of vasodilatory hypotension in patients with vasodilatory shock has also improved over the years with the usage of arginine vasopressin.^{23,24} The vasoconstrictive effect of arginine vasopressin reduces the dependence on catecholamines, such as dopamine and epinephrine, which has the potential to increase arrhythmogenicity of myocardial tissue in patients who are already prone to develop malignant ventricular arrhythmias. An additional benefit of vasopressin involves its effect on the kidneys. Possibly due to selective constriction of the efferent arteriole (without constriction of the afferent arteriole), vasopressin increases urine output in patients with septic shock.²⁴

Although the development of circulating antibodies, termed "sensitization," does not impact early perioperative LVAD morbidity and mortality, it has significant adverse long-term effects.^{25,26} LVAD recipients have prominent B-cell activation, as evidenced by heightened production of

TABLE 3. Device malfunction for different devices

	PNEUM	DLVE	SLVE
Overall incidence	8 (15.4%)	5 (29.4%)	18 (10.3%)
Clinically significant malfunctions only	6 (11.5%)	4 (23.5%)	10 (5.7%)
Electrical			
Faulty display on console	2		
Pump defaulted to fixed rate		1	
Faulty alarming system			
Pump stopped, requiring pneumatic backup		1	1
Malfunction of transistor commutator			1
Software malfunction			
Mechanical			
Tear in Perc lead	1	1	1
Inflow regurgitation	0	1	2
Inflow regurgitation noted at explantation			1
Fractured vent adapter			1
Technical			
Bleeding between outflow graft and valve	1		1
Bleeding between inflow graft and valve			1
Kinking on inflow graft			1
Other			
Hole in inflow graft near valve	1		
Hole in outflow graft near valve	1		
Noted at explantation			
Hole in outflow graft near valve	2	1	4
Hole in inflow graft near valve			3
Hole in inflow valve			1
Mean duration to device malfunction (days)	66.2 ± 29.1	213.1 ± 178.6	95.4 ± 68.9
Median duration to device malfunction (days)	65.2	134.4	62.5

PNEUM, Pneumatic device; DLVE, Dual-lead vented electric device; SLVE, single-lead vented electric device.

anti-human leukocyte antigen class I and II immunoglobulin G antibodies.²⁶ As a result of these circulating antibodies, LVAD recipients are subject to repeated positive cross-matches, increased waiting time to cardiac transplant (with

TABLE 4. Incidence of CVA and TIA while on LVAD support

Neurological complication	PNEUM	DLVE	SLVE	P*
CVA	4 (7.7%)†	2 (11.8%)	7 (4.0%)	.443
TIA	0	0	11 (6.3%)	.223

CVA, Cerebrovascular accident (stroke); TIA, transient ischemic attack; LVAD, left ventricular assist device; PNEUM, pneumatic device; DLVE, dual-lead vented electric device; SLVE, single-lead vented electric device.

*P values from chi-square analysis.

†Absolute number (percentage of total).

TABLE 5. Univariate analysis of factors affecting successful bridging to transplant

Variable	P
Age	.080
Gender	.001
Race	
Caucasian	.751
African American	.383
Other	.407
Device type	
PNEUM	.571
DLVE	.901
SLVE	.763
Etiology of heart failure	
CAD	.044
ICM	.003
Other	.048
Duration of support	<.001
Device malfunction	.412
Infection	.111
Drive line	.530
Pocket	.095
Pump	.557
LVAD score	<.001

PNEUM, Pneumatic device; DLVE, dual-lead vented electric device; SLVE, single-lead vented electric device; CAD, coronary artery disease; ICM, idiopathic cardiomyopathy; LVAD, left ventricular assist device.

TABLE 6. Factors affecting successful bridging to transplant using multivariate, stepwise logistic regression

Variable	OR	95% CI	P	SE
LVAD score	1.214	1.119-1.316	<.001	0.041

OR, Odds ratio; CI, confidence interval; SE, standard error; LVAD, left ventricular assist device.

the risk of increased waiting list mortality), and increased risk of cellular rejection after transplantation.²⁵ We previously reported that 66% of Thoratec HeartMate LVAD recipients at our institution were sensitized.²⁷ Early in our experience (1992-1996), we noted the development and subsequent deleterious effects of sensitization in LVAD recipients. We therefore devised and instituted a treatment

regimen consisting of cyclophosphamide and intravenous immunoglobulin for all sensitized patients beginning in 1997. The use of this immunomodulatory therapy reduced both the waiting time and risk of acute rejection in sensitized recipients.²⁷ Because of the increased frequency of sensitization among Thoratec HeartMate LVAD recipients, it is important that panel-reactive antibody testing be performed at regular intervals. It has been suggested that sensitized patients may be at risk for the development of anti-human leukocyte antigen antibodies in the posttransplant period, thereby potentially contributing to deleterious effects on the cardiac allograft. Thus, these patients may merit closer follow-up and more targeted immunosuppression.

The HeartMate Thoratec is the preferred device at our institution for long-term support as a bridge to transplantation. Its advantages include portability and mobility, along with lower cost of support by allowing patients to be discharged from the hospital.²⁸ Additionally, long-term anticoagulation is not required with the HeartMate, although it is possible that with judicious use of postoperative anticoagulation, the incidence of CVAs and TIAs may be decreased. This, however, requires further analysis in a randomized trial. Design improvements that have contributed to better device performance include transformation to a single percutaneous lead, outflow graft bend relief, a smaller and more flexible percutaneous cable, additional inflow valve anchoring sutures, and the Opti-Fill software.³

The main limitations to the HeartMate device, however, is that it is a univentricular support system and requires cardiopulmonary bypass for insertion as inflow must originate from the left ventricular apex. Its application is also limited in small-sized patients (body surface area < 1.5 m²) secondary to size requirements of the device, where other devices may be considered.^{29,30}

Limitations of this study include those related to a retrospectively performed analysis. Clinical data were obtained by chart review, which has inherent limitations, such as access and accuracy of the data. Additionally, as a retrospective observational study, it is subject to selection bias and incomplete data collection. Finally, extrapolation of the results regarding improved success in bridging patients to transplant and posttransplant survival with the HeartMate is limited because of interinstitutional variability in clinical practice.

In conclusion, although the paradigm for assist devices may shift to a bridge to recovery or destination therapy, the role of an LVAD as a bridge to transplantation for patients with end-stage heart failure will remain an important one.³¹⁻³³ In reviewing our institutional experience, we noted progressive improvements in bridging to transplantation success and posttransplant survival. Improvements in these outcome measures over the last 12 years occurred as a result

Figure 3. Bridging to transplant success based on preimplantation LVAD scores. LVAD scores were categorized as low (0-4), medium (5-7), and high (8-10).

TABLE 7. Changes in clinical practice that have occurred along with temporal changes in device design

Preoperative	Intraoperative	Postoperative
IABP	Aprotinin	Nitric oxide
Early LVAD implantation	Biogluce	Phosphodiesterase inhibitors (Milrinone)
Optimize fluid status	Nitric oxide	Aggressive use of RVADs for RV failure
Broad-spectrum antibiotics	Phosphodiesterase inhibitors (Milrinone)	Avoid excessive blood products
	Screening for PFO	Early institution of CVVH
	Modification of outflow tract anastomosis	Arginine vasopressin
	Vancomycin around preperitoneal pocket	Improved ICU care
		IMT for sensitized patients

IABP, Intra-aortic balloon pump; LVAD, left ventricular assist device; PFO, patent foramen ovale; RVAD, right ventricular assist device; RV, right ventricle; CVVH, continuous veno-venous hemofiltration; ICU, intensive care unit; IMT, immunomodulatory therapy.

of improved patient selection as well as many major advances in preoperative, intraoperative, and postoperative clinical practices. During this time period, there were also temporal improvements in device design. Our challenge is to continue to improve upon patient selection and perioperative management, as well to design smaller, infection-resistant, more durable devices to make LVADs increas-

ingly more effective in bridging patients with end-stage heart failure to transplantation.

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References

1. Reis SE, Holubkov R, Edmundowicz D, et al. Treatment of patients admitted to the hospital with congestive heart failure: specialty-related disparities in practice patterns and outcomes. *J Am Coll Cardiol*. 1997;30:733-8.
2. Stevenson WG, Stevenson LW, Middlekauff HR, et al. Improving survival for patients with advanced heart failure: a study of 737 consecutive patients. *J Am Coll Cardiol*. 1995;26:1417-23.
3. Mavroidis D, Sun BC, Pae WE Jr. Bridge to transplantation: the Penn State experience. *Ann Thorac Surg*. 1999;68:684-7.
4. Peterze B, Lonn U, Jansson K, Rutberg H, Casimir-Ahn H, Nylander E. Long-term follow-up of patients treated with an implantable left ventricular assist device as an extended bridge to heart transplantation. *J Heart Lung Transplant*. 2002;21:604-7.
5. Portner PM, Jansen PG, Oyer PE, Wheeldon DR, Ramasamy N. Improved outcomes with an implantable left ventricular assist system: a multicenter study. *Ann Thorac Surg*. 2001;71:205-9.
6. Williams MR, Oz MC. Indications and patient selection for mechanical ventricular assistance. *Ann Thorac Surg*. 2001;71:S86-91.
7. Pennington DG, McBride LR, Peigh PS, Miller LW, Swartz MT. Eight years' experience with bridging to cardiac transplantation. *J Thorac Cardiovasc Surg*. 1994;107:472-81.
8. El-Banayosy A, Korfer R, Arusoglu L, et al. Device and patient management in a bridge-to-transplant setting. *Ann Thorac Surg*. 2001;71:S98-102.
9. Sun BC, Catanese KA, Spanier TB, et al. 100 long-term implantable left ventricular assist devices: the Columbia Presbyterian interim experience. *Ann Thorac Surg*. 1999;68:688-94.
10. Frazier OH, Rose EA, Oz MC, et al. Multicenter clinical evaluation of the HeartMate vented electric left ventricular assist system in patients awaiting heart transplantation. *J Thorac Cardiovasc Surg*. 2001;122:1186-95.
11. El-Banayosy A, Arusoglu L, Kizner L, et al. Novacor left ventricular assist system versus Heartmate vented electric left ventricular assist system as a long-term mechanical circulatory support device in bridging patients: a prospective study. *J Thorac Cardiovasc Surg*. 2000;119:581-7.
12. McCarthy PM, Smedira NO, Vargo RL, et al. One hundred patients with the HeartMate left ventricular assist device: evolving concepts and technology. *J Thorac Cardiovasc Surg*. 1998;115:904-12.
13. Holman WL, Davies JE, Rayburn BK, et al. Treatment of end-stage heart disease with outpatient ventricular assist devices. *Ann Thorac Surg*. 2002;73:1489-94.
14. Morales DL, Catanese KA, Helman DN, et al. Six-year experience of caring for forty-four patients with a left ventricular assist device at home: safe, economical, necessary. *J Thorac Cardiovasc Surg*. 2000;119:251-9.
15. DeRose JJ Jr, Umana JP, Argenziano M, et al. Implantable left ventricular assist devices provide an excellent outpatient bridge to transplantation and recovery. *J Am Coll Cardiol*. 1997;30:1773-7.
16. Rao V, Oz MC, Flannery MA, Catanese KA, Argenziano M, Naka Y. Revised screening scale to predict survival after insertion of a left ventricular assist device. *J Thorac Cardiovasc Surg*. 2003;125:855-62.
17. Oz MC, Argenziano M, Catanese KA, et al. Bridge experience with long-term implantable left ventricular devices: are they an alternative to transplantation? *Circulation*. 1997;95:1844-52.
18. Kavarana MN, Pessin-Minsley MS, Urtecho J, et al. Right ventricular dysfunction and organ failure in left ventricular assist device recipients: a continuing problem. *Ann Thorac Surg*. 2002;73:745-50.
19. Argenziano M, Choudhri AF, Moazami N, et al. Randomized, double-blind trial of inhaled nitric oxide in LVAD recipients with pulmonary hypertension. *Ann Thorac Surg*. 1998;65:340-5.
20. Goldstein DJ, Seldomridge JA, Chen JM, et al. Use of aprotinin in LVAD recipients reduces blood loss, blood use, and perioperative mortality. *Ann Thorac Surg*. 1995;59:1063-8.
21. Kukuy EL, Goldstein DJ, Rao V, Edwards NM, Naka Y. A simple method of creating LVAD outflow tract aortic anastomosis. *Heart Surg Forum*. 2002;6:53-4.
22. Kukuy EL, Kherani AR, Fal JM, et al. Prophylactic antibiotic paste reduces left ventricular assist device pocket infections. *Heart Surg Forum*. 2003;6:111.
23. Argenziano M, Choudhri AF, Oz MC, Rose EA, Smith CR, Landry DW. A prospective randomized trial of arginine vasopressin in the treatment of vasodilatory shock after left ventricular assist device placement. *Circulation*. 1997;96:II-286-90.
24. Landry DW, Oliver JA. The pathogenesis of vasodilatory shock. *N Engl J Med*. 2001;345:588-95.
25. Itescu S, Tung TC, Burke EM, et al. Preformed IgG antibodies against major histocompatibility class II antigens are major risk factors for high grade cellular rejection in recipients of heart transplantation. *Circulation*. 1998;98:786-93.
26. Schuster M, Kocher A, John R, et al. B cell activation and allosensitization after left ventricular assist device implantation is due to T cell activation and CD40 ligand expression. *Hum Immunol*. 2002;63:211-20.
27. John R, Lietz K, Schuster M, et al. Immunologic sensitization in recipients of left ventricular assist devices. *J Thorac Cardiovasc Surg*. 2003;125:578-91.
28. Morales DL, Catanese KA, Helman DN, et al. Six-year experience of caring for forty-four patients with a left ventricular assist device at home: safe, economical, necessary. *J Thorac Cardiovasc Surg*. 2000;119:251-9.
29. Farrar DJ, Hill JD, Pennington DG, 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;113:202-9.
30. Korfer R, El-Banayosy A, Arusoglu L, et al. Single-center experience with the Thoratec ventricular assist device. *J Thorac Cardiovasc Surg*. 2000;119:596-600.
31. Rose EA, Gelijns AC, Moskowitz AJ, et al. Randomized Evaluation of Mechanical Assistance for the Treatment of Congestive Heart Failure (REMATCH) Study Group. Long-term mechanical left ventricular assistance for end-stage heart failure. *N Engl J Med*. 2001;345:1435-43.
32. Hetzer R, Muller JH, Weng YG, Loebe M, Wallukat G. Midterm follow-up of patients who underwent removal of a left ventricular assist device after cardiac recovery from end-stage dilated cardiomyopathy. *J Thorac Cardiovasc Surg*. 2000;120:843-53.
33. Frazier OH, Myers TJ. Left ventricular assist system as a bridge to myocardial recovery. *Ann Thorac Surg*. 1999;68:734-41.