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EXPEDITED PUBLICATION

The Percutaneous Ventricular Assist Device in Severe Refractory Cardiogenic Shock

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Objectives We evaluated the efficacy and safety of the percutaneous ventricular assist device (pVAD) in patients in severe refractory cardiogenic shock (SRCS) despite intra-aortic balloon pump (IABP) and/or high-dose vasopressor support.

Background SRCS is associated with substantial mortality despite IABP counterpulsation. Until recently, there was no rapid, minimally invasive means of providing increased hemodynamic support in SRCS.

Methods A total of 117 patients with SRCS implanted with TandemHeart pVAD (CardiacAssist, Inc., Pittsburgh, Pennsylvania) were studied, of whom 56 patients (47.9%) underwent active cardiopulmonary resuscitation immediately before or at the time of implantation. Data was collected regarding clinical characteristics, hemodynamics, and laboratory values.

Results Eighty patients had ischemic and 37 patients had nonischemic cardiomyopathy. The average duration of support was 5.8 ± 4.75 days. After implantation, the cardiac index improved from median 0.52 (interquartile range [IQR]: 0.8) l/(min·m^2) to 3.0 (IQR: 0.9) l/(min·m^2) ($p < 0.001$). The systolic blood pressure and mixed venous oxygen saturation increased from 75 (IQR: 15) mm Hg to 100 (IQR: 15) mm Hg ($p < 0.001$) and 49 (IQR: 11.5) to 69.3 (IQR: 10) ($p < 0.001$), respectively. The urine output increased from 70.7 (IQR: 70) ml/day to 1,200 (IQR: 1,620) ml/day ($p < 0.001$). The pulmonary capillary wedge pressure, lactic acid level, and creatinine level decreased, respectively, from 31.53 ± 10.2 mm Hg to 17.29 ± 10.82 mm Hg ($p < 0.001$), 24.5 (IQR: 74.25) mg/dl to 11 (IQR: 92) mg/dl ($p < 0.001$), and 1.5 (IQR: 0.95) mg/dl to 1.2 (IQR: 0.9) mg/dl ($p = 0.009$). The mortality rates at 30 days and 6 months were 40.2% and 45.3%, respectively.

Conclusions The pVAD rapidly reversed the terminal hemodynamic compromise seen in patients with SRCS refractory to IABP and vasopressor support. (J Am Coll Cardiol 2010;xx:000–00) © 2010 by the American College of Cardiology Foundation

In patients with ischemic cardiomyopathy (ICM) and cardiogenic shock, the mortality rate ranges from 55% to 73% despite intra-aortic balloon pump (IABP) counterpulsation and coronary reperfusion (1–5). Patients with nonischemic cardiomyopathy (NICM) and cardiogenic shock are also at increased risk for cardiovascular death (6), although this increase is not as well documented. For patients with either ICM or NICM and cardiogenic shock, prompt reversal of hypoperfusion is essential to support organ function during post-treatment myocardial recovery and to stabilize the patient for definitive percutaneous or surgical intervention.

Although various pharmacological and mechanical methods are available for maintaining hemodynamic support in patients with severely depressed left ventricular function, all of these methods have their limitations. The most commonly used form of support is IABP counterpulsation. However, the IABP is often inadequate to reverse hemodynamic compromise in patients with severe refractory cardiogenic shock (SRCS). In patients presenting with SRCS, the mortality rate ranges from 52% to 76% (7–9).

Although complete hemodynamic support is possible with surgically placed systems such as cardiopulmonary support devices and left ventricular assist devices (LVADs), these are themselves associated with significant morbidity and death (10–12). Currently, the TandemHeart percutaneous ventricular assist device (pVAD) (CardiacAssist, Inc., Pittsburgh, Pennsylvania), a minimally invasive,

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Abbreviations and Acronyms

CAD = coronary artery disease

CPR = cardiopulmonary resuscitation

IABP = intra-aortic balloon pump

ICM = ischemic cardiomyopathy

IQR = interquartile range

LVAD = left ventricular assist device

MAP = mean arterial pressure

NICM = nonischemic cardiomyopathy

pVAD = percutaneous ventricular assist device

SRCS = severe refractory cardiogenic shock

STEMI = ST-segment elevation myocardial infarction

continuous-flow device capable of complete hemodynamic support, is available. The TandemHeart pVAD can be inserted quickly, in the catheterization laboratory, to provide temporary mechanical circulatory support until more definitive therapies can be pursued.

In light of the high mortality rate of cardiogenic shock patients and the limitations of the IABP, we sought to determine the efficacy of the pVAD for hemodynamic support in patients with ICM or NICM that was refractory to IABP and pressor support.

Methods

From May 2003 through November 2008, 117 consecutive patients with either ICM or NICM and SRCS received pVADs (Table 1). This included 80 men and 37 women with an average age of 55.37 ± 15.6 years. Eighty patients had ICM, and 37 had NICM. The median initial left ventricular ejection fraction for the 2 groups was 20.5% (interquartile range [IQR]: 5%) and 36% (IQR: 25%), respectively.

All patients were categorized as having either ICM or NICM based on presence or absence of occlusive disease on cardiac catheterization (Fig. 1).We categorized patients in the ICM group if they had a history of a previous myocardial infarction secondary to occlusive coronary artery disease (CAD), previous percutaneous or surgical revascularization, or evidence of occlusive CAD during cardiac catheterization at the time of cardiogenic shock. Patients whose catheterization studies were negative for occlusive CAD were assigned to the NICM group. Only 5 of 80 patients in the ICM group were undergoing active ST-segment elevation myocardial infarction (STEMI) at the time of implantation and included patients with severe complications such as post-infarct ventricular septal defect, incessant ventricular tachycardia (VT) storm, and primary pump failure. All other patients had chronic ICM/NICM.

All hemodynamic (except pVAD flow rate) and biochemical parameters post-implantation were measured at 24 h after implantation or last available biochemical parameters in case of death before 24 h after implantation. Flow rates were measured at 1 h after implantation.

The ICM group comprised 61 men and 19 women with an average age of 61.8 ± 11.0 years. Forty-eight patients (60%) had previously been diagnosed with STEMI, and 32 patients (40%) had been diagnosed with non–ST-segment elevation myocardial infarction. Most patients (64 of 80; 80.0%) had previously revascularized CAD, including left main disease; angiography showed an average of 2.6 involved vessels that needed intervention.

The NICM group was composed of 19 men and 18 women with an average age of 41.4 ± 14.8 years and predominantly dilated cardiomyopathy (10 of 37; 27%) and myocarditis (9 of 37; 24.3%).

SRCS was characterized by a systolic blood pressure of <90 mm Hg, a cardiac index of <2.0 l/(min·m^2) and evidence of end-organ failure despite IABP/pressor support. Informed consent was obtained from the surrogate decision makers of all the patients studied. We prospectively collected data regarding clinical factors and characteristics, hemodynamic values, laboratory values, medications, and

Table 1 Patient Baseline Characteristics

Total patients, n	117
Age, yrs	55.37 ± 15.576
Male sex	80 (68.4%)
Left ventricular ejection fraction	20 (IQR: 5)
Vasopressors, n	2.1 ± 1.2
Ischemic cardiomyopathy	80 (68.4%)
STEMI	48 (60%)
NSTEMI	32 (40%)
Previous myocardial infarction	64 (80%)
Previous PCI/ACB	64 (80%)
No. of vessels with occlusive CAD	2.6
Diabetes mellitus	33 (41.2%)
Hypertension	54 (67.5%)
Hyperlipidemia	54 (67.5%)
Chronic kidney disease	40 (50%)
Current or former smoker	38 (47.5%)
Previous CVA/TIA	7 (8.8%)
Peripheral vascular disease	16 (20%)
Nonischemic cardiomyopathy	37 (31.6%)
Idiopathic dilated cardiomyopathy	10 (27.27%)
Myocarditis	9 (24.32%)
Valvular diseases	7(18.91)
Grade 2R orthotopic heart transplant rejection	3 (8.1%)
Restrictive cardiomyopathy	3 (8.1%)
Peripartum cardiomyopathy	1 (2.7%)
Sarcoid cardiomyopathy	1 (2.7%)
Alcoholic cardiomyopathy	1 (2.7%)
Takotsubo cardiomyopathy	1 (2.7%)
Angiosarcoma	1 (2.7%)
Intra-aortic balloon pump	96 (82.1%)
Ischemic cardiomyopathy	69/80 (86.2%)
Nonischemic cardiomyopathy	27/37 (73%)
Undergoing CPR	56 (47.9%)
Ischemic cardiomyopathy	41/80 (51.2%)
Nonischemic cardiomyopathy	15/37 (40.5%)
Mechanical ventilation	54 (46.2%)
AICD	39 (33.3%)

Data are n (%) unless otherwise stated.

ACB = aortocoronary bypass; AICD = automated implantable cardioverter-defibrillator; CAD = coronary artery disease; CPR = cardiopulmonary resuscitation; CVA = cerebrovascular accident; NSTEMI = non–ST-segment elevation myocardial infarction; PCI = percutaneous coronary intervention; STEMI = ST-segment elevation myocardial infarction; TIA = transient ischemic attack.

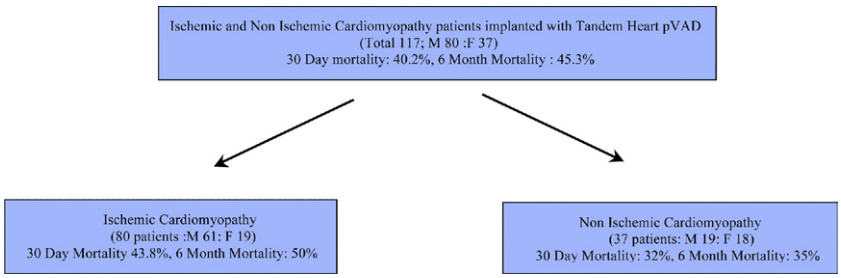

Figure 1 **Overall Study Design and Results**

A total of 117 patients (80 with ischemic and 37 with nonischemic cardiomyopathy) with severe refractory cardiogenic shock were implanted with TandemHeart percutaneous ventricular assist device (pVAD).

diagnostic tests. Post-hospitalization follow-up information was obtained for all patients for at least 6 months after pVAD placement. As in previous studies (13–15), the following values were imputed to patients who were undergoing active cardiopulmonary resuscitation: a cardiac index of 0 l/(min·m2), systolic blood pressure of 60 mm Hg, and diastolic blood pressure of 20 mm Hg. This was done to highlight adequacy of manual compressions to maintain cerebral perfusion.

The TandemHeart and its method of implantation have been described elsewhere (16). Briefly, the TandemHeart is a continuous-flow pump that can be inserted percutaneously, in the cardiac catheterization laboratory. All devices are inserted by a board-certified interventional cardiologist. A 21-F left atrial cannula, inserted by means of a venous trans-septal puncture via the femoral vein, channels blood into the pump, and a 15- to 17-F femoral artery cannula carries the blood to the systemic arterial circulation. The size of the outflow cannula is selected after peripheral angiography. The TandemHeart is capable of up to 4.5 l/min of assisted cardiac output. Heparin is administered continuously to achieve a targeted activated partial thromboplastin time of 60 to 80 s.

In our center, patients with cardiogenic shock are placed on escalating doses of vasopressors (dopamine, norepinephrine, vasopressin, epinephrine, phenylephrine) to maintain viable hemodynamic status. The choice of vasopressors was tailored for each patient depending on their rapidly changing hemodynamic status as well as the initial vasopressor regimen before transfer to our center. Patients not stabilized on low-dose vasopressors are transitioned onto an IABP followed by high-dose vasopressors. Patients with SRCS despite high-dose vasopressors and IABP were transitioned to the pVAD. A few patients with severe cardiovascular complications like post-infarct ventricular septal defect with unstable hemodynamics/incessant VT storm were directly transitioned to pVAD. Almost all the patient were on systemic anticoagulation as well as diuretics. Patients requiring right ventricular support were supported with milrinone/dobutamine/epoprostenol sodium. Figure 2 highlights the strategy used in acute cardiopulmonary failure at our institute.

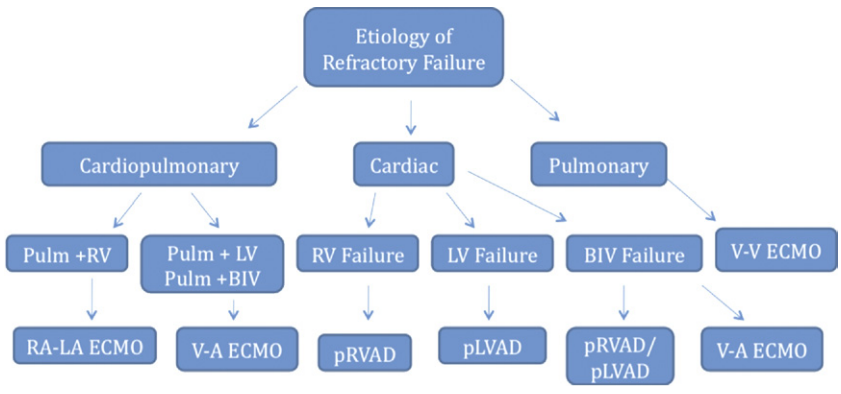

Figure 2 **Strategy for Acute Cardiopulmonary Failure: Texas Heart Institute Experience**

This reflects the strategy for acute cardiopulmonary failure at our center. Decision regarding the type of device to be used is based on cardiac/pulmonary/cardiopulmonary failure as well as right ventricular (RV)/left ventricular (LV)/biventricular (BIV) failure. ECMO = extracorporeal membrane oxygenation; LA = left atrial; pLVAD = percutaneous left ventricular assist device; pRVAD = percutaneous right ventricular assist device; V-A = venoatrial; V-V = venovenous.

Patients were weaned off TandemHeart pVAD based on serial real-time assessment of their hemodynamics and end-organ function. The pVAD flow rate was constantly adjusted to maintain mixed venous oxygen saturation >70 and mean arterial pressure (MAP) >60 mm Hg and to facilitate aortic valve opening. Patients showing adequate hemodynamics and improving end-organ function at pVAD flow rate of 2 l/day for 2 days were gradually weaned off the pVAD. Those who did not meet the above criteria were transitioned to LVAD/transplant. The decision to bridge to LVAD/transplant/recovery was based on several factors, including post-device placement course, complications, hemodynamic status, and overall suitability as a candidate for LVAD/transplant.

In this study, mean values and SDs for continuous variables were determined with SPSS version 18 (SPSS Inc., Chicago, Illinois). A p value of <0.05 was considered significant. Categorical variables were presented and compared as numbers and percentages. The distribution of all variables was tested for normality, and nonparametric testing was done to analyze them. All skewed parameters have been represented by median and IQR, whereas all nonskewed parameters have been described as mean ± SD. Paired *t* tests were used for analysis between continuous nonskewed variables and nonparametric testing using medians for skewed variables. Univariate and multivariate analysis was done using logistic regression between survivors and nonsurvivors and was adjusted for age, IABP, preimplantation cardiopulmonary resuscitation (CPR), preimplantation creatinine, pre-implantation pressor use, and pre-implantation MAP. Kaplan-Meier survival analysis was used to analyze survival and was sub-stratified for cardiomyopathy and treatment arm.

Results

In the overall group, 96 patients (82.1%) were receiving IABP support before pVAD placement. The 21 patients (11 with ICM, 10 with NICM) who did not undergo IABP counterpulsation required continuous CPR (average cardiac index, 0 l/[min·m^2]) and were deemed beyond hemodynamic salvage with the addition of IABP support alone, so pVADs were emergently placed. Fifty-six (47.9%) of the 117 patients (41 of 80 [51.2%] with ICM; 15 of 37 [40.5%] with NICM) were undergoing CPR during pVAD placement.

The reason for initiating CPR was pulseless VT in 50%, ventricular fibrillation in 27.8%, pulseless electrical activity in 14.8%, bradycardic arrest in 5.55%, and asystole in 1.8%. All of the arrests occurred before the device was implanted. Some of them were in the field before the patients were airlifted to our facility; others were in the emergency room, critical care unit, and catheterization lab. The average time from CPR onset to TandemHeart implantation was 65.6 ± 41.3 min. On an average it took 15 to 65 min to implant the TandemHeart. After device placement the decision to transition to LVAD was based on several factors, including post-device placement course, complications, hemodynamic status, and overall suitability as a candidate for LVAD. Eight patients were discovered to have a neurological insult/stroke, of which three had the pVAD replaced (1 with another pVAD, 1 with Levitronix and 1 with Heartmate II LVAD) and later survived to discharge. Thirty one patients had multi organ failure after device placement, of which fourteen survived to discharge, with three undergoing transplantation, and four being transitioned to other LVAD's (Levitronix, HeartMate XVE, HeartMate II, Ex-

Table 2 Hemodynamic and Biochemical Values in All Patients in Cardiogenic Shock

Value	Pre-pVAD	With pVAD	p Value
Cardiac index, l/(min·m^2)	0.52 (IQR: 0.8)	3.0 (IQR: 0.9)	<0.001
Systolic blood pressure, mm Hg	75 (IQR: 15)	100 (IQR: 15)	<0.001
Diastolic blood pressure, mm Hg	30 (IQR: 20)	65 (IQR: 20)	<0.001
Mean arterial pressure, mm Hg	45 (IQR: 20)	81 (IQR: 15)	<0.001
Heart rate, beats/min	105.1 ± 18.0	85.7 ± 12.9	<0.001
SVO_2, %	49 (IQR: 11.5)	69.29 (IQR: 10)	<0.001
PCWP, mm Hg	31.52 ± 10.20	17.29 ± 10.82	<0.001
Pulmonary arterial pressure, mm Hg	39.16 ± 12.10	26.70 ± 7.99	<0.001
Lactic acid, mg/dl	24.5 (IQR: 74.25)	11.0 (IQR: 12)	<0.001
LDH, U/dl	602 (IQR: 630)	416.5 (IQR: 335)	0.101
pH	7.22 ± 0.14	7.44 ± 0.06	<0.001
Creatinine, mg/dl	1.5 (IQR: 0.95)	1.2 (IQR: 0.9)	0.009
BUN, mg/dl	39.72 ± 17.88	30.35 ± 15.54	0.108
Urine output, ml/day	70.3 (IQR: 70)	1200 (IQR: 1620)	<0.001
Hemoglobin	11 (IQR: 2.65)	10.25 (IQR: 1.8)	<0.001
AST	125 (IQR: 363.75)	75 (IQR: 169)	0.02
ALT	75 (IQR: 317)	55.5 (IQR: 316.75)	0.06

ALT = alanine transaminase; AST = aspartate transaminase; BUN = blood urea nitrogen; IQR = interquartile range; LDH = lactate dehydrogenase; PCWP = pulmonary capillary wedge pressure; pVAD = percutaneous ventricular assist device; SVO_2 = mixed venous oxygen saturation.

Table 3 Hemodynamic and Biochemical Values in ICM and NICM Patients in Cardiogenic Shock

	Ischemic Cardiomyopathy			Nonischemic Cardiomyopathy		
Value	Pre-pVAD	With pVAD	p Value	Pre-pVAD	With pVAD	p Value
CI, l/min·m^2	0.4 (IQR: 0.7)	2.8 (IQR: 0.5)	<0.001	0.7 (IQR: 0.9)	3.9 (IQR: 1.87)	<0.001
SBP, mmHg	80 (IQR: 20)	100 (IQR: 20)	<0.001	75 (IQR: 15)	100 (IQR: 15)	<0.001
DBP, mmHg	30 (IQR: 20)	70 (IQR: 15)	<0.001	35 (IQR: 15)	65 (IQR: 20)	0.003
MAP, mmHg	40 (IQR: 32)	82.5 (IQR: 15)	<0.001	55 (IQR: 15)	80.5 (IQR: 10)	<0.001
HR, beats/min	102.9 ± 21.5	84.6 ± 11.3	0.002	108.6 ± 10.9	88.2 ± 14.6	<0.001
SVO_2, %	45 (IQR: 13)	69 (IQR: 13)	0.002	53 (IQR: 10)	70 (IQR: 14)	0.05
PCWP, mmHg	29.81 ± 10.27	16.0 ± 6	<0.001	33.18 ± 10.09	18.38 ± 13.85	0.001
Pulmonary arterial pressure, mm Hg	39.86 ± 14.46	26.5 ± 8.78	0.007	38.43 ± 9.33	28.12 ± 8.34	0.011
Lactic acid, mg/dl	24 (IQR: 66)	11(IQR: 9)	0.001	36 (IQR: 83)	14 (IQR: 8.5)	0.05
LDH, U/dl	546 (IQR: 692)	421 (IQR: 383)	0.229	627 (IQR: 697)	384 (IQR: 290)	0.089
pH	7.23 ± 0.15	7.46 ± 0.65	<0.001	7.21 ± 0.14	7.42 ± 0.7	0.003
Creatinine, mg/dl	1.5 (IQR: 1.15)	1.3 (IQR: 0.9)	0.111	1.6 (IQR: 0.9)	1.15 (IQR: 0.85	0.024
BUN, mg/dl	37.08 ± 15.59	31.27 ± 14.95	0.37	45.0 ± 22.42	28.67 ± 17.86	0.19
Urine output, ml/day	62 (IQR: 64.5)	1,150 (IQR: 800)	<0.001	74.5 ± 65.0	1,390 ± 870	<0.001
EF, %	20 (IQR: 5)	36 (IQR: 28)	<0.001	20 (IQR: 6)	30 (IQR: 25)	0.08
Hemoglobin, g/dl	10.9 (IQR: 2.8)	10.1 (IQR: 1.8)	0.058	11 (IQR: 2.5)	10.5 (IQR: 2.6)	0.04
AST	141 (IQR: 360)	66 (IQR: 132)	0.023	100 (IQR: 646)	68 (IQR: 367)	0.211
ALT	75 (IQR: 266)	51 (IQR: 106)	0.110	85 (IQR: 667)	49.5 (363)	0.309

CI = cardiac index; DBP = diastolic blood pressure; EF = ejection fraction; ICM = ischemic cardiomyopathy; IQR: = interquartile range; NICM = nonischemic cardiomyopathy; SBP = systolic blood pressure; other abbreviations as in Table 2.

tra Corporeal Membrane Oxygenator). The other 17 of 31 patients with multiorgan failure died.

The average number of pressor agents used was 2.1 ± 1.2. Each agent was titrated to maximal dosing before initiation of additional vasopressors. The mean time from the onset of cardiogenic shock to placement of a pVAD was 2.6 ± 3.0 days in both the ICM and NICM groups. The average duration of pVAD support was 5.8 ± 4.75 days. The average pVAD flow rate was 3.29 ± 0.7 l/min at 1 h after implantation.

Hemodynamic and biochemical values. There was significant improvement in all hemodynamic values, an increase in mixed venous oxygen saturation and urine output, and a concurrent decline in creatinine and blood urea nitrogen levels in the overall cohort after implantation of the pVAD (Table 2). Similar improvements in hemodynamic and biochemical values were also seen separately in both the ICM and NICM groups (Table 3). There was a significant decrease in the lactic acid level, both overall and within each group.

In-hospital treatment and outcomes. Thirteen patients underwent percutaneous or surgical revascularization. Thirty-one patients went on to LVAD placement, and 5 patients underwent orthotopic heart transplantation; the remaining patients were treated medically. The total mortality rate was 40.2% at 30 days and 45.3% at 6 months. In the ICM group, the 30-day and 6-month mortality rates were 43.8% and 50%, respectively. Mortality rates in the NICM group were 32% and 35% at 30 days and 6 months, respectively. Twenty-four (43%) of the 56 patients who had undergone resuscitation during pVAD placement were alive at 30 days, and 21 (36.5%) were alive at 6 months. Twenty-four patients (50%) who presented with STEMI in the ICM group were alive at 30 days, and 21 (44.75%) were alive at 6 months. Twenty-four of the 31 patients (77.4%) who received an LVAD were alive at 30 days, and 21 patients (67.7%) were alive at 6 months. The Kaplan-Meier survival curves for the overall group (Fig. 3), ICM versus NICM (Fig. 4), and stratified by treatment subgroup (Fig. 5) are provided.

Safety and efficacy. Complications included 1 wire-mediated perforation of the left atrium. The device was successfully implanted, and the patient underwent emergent surgical repair while the pVAD provided left atrial unloading and hemodynamic support, but the patient later died of post-operative complications. Another patient had a right common femoral artery dissection that required surgical repair. Groin hematomas occurred in 6 patients (5.12%) and bleeding around cannula site occurred in 34 of 117 patients (29.05%), whereas device-related limb ischemia was seen in 4 patients (3.41%). The post-implantation course was complicated by sepsis/systemic inflammatory response syndrome in 29.9%, gastrointestinal bleeding in 19.65%, coagulopathy in 11%, and stroke in 6.8% of patients. Blood transfusions were needed in 70 patients (57 of 80) [71%] patients with ICM; 13 of 37 [35.1%] patients with NICM). Details on the safety of the device are listed in Table 4.

Analysis of survivors and nonsurvivors. After pVAD placement, survivors had significant improvement in all hemodynamic and most biochemical values, including lactic acid, whereas nonsurvivors had no significant decrease in lactic acid despite significant improvement in hemodynamic values. Nonsurvivors were older ($p = 0.013$), had higher rates of CPR ($p < 0.001$), and were on a higher number of

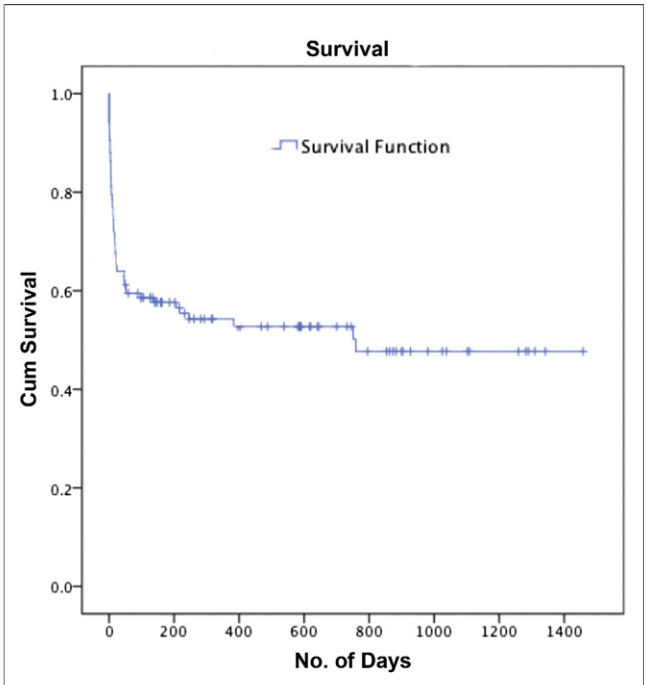

Figure 3 **Survival Analysis of All Patients**

Kaplan-Meier survival curve of 117 patients showing survival at 30 days, 6 months, and last follow-up.

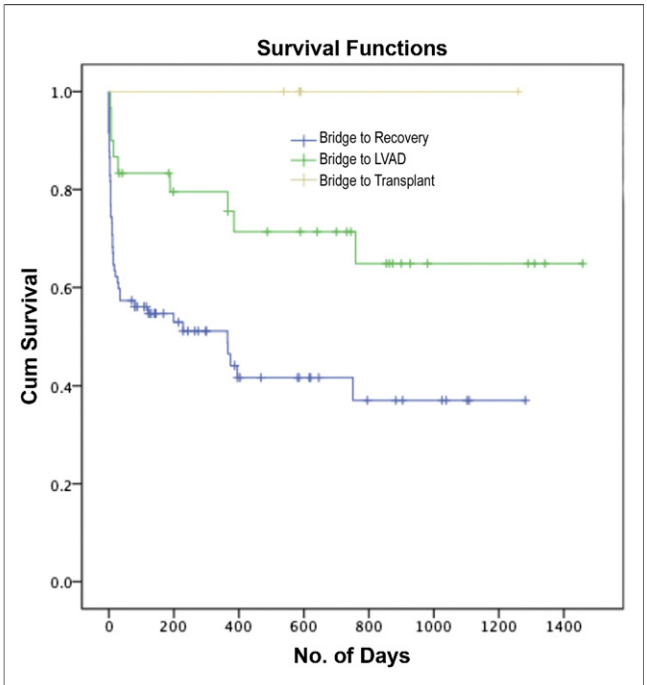

Figure 5 **Survival Analysis Stratified by Bridge to Transplant, Bridge to LVAD, and Bridge to Recovery**

Kaplan-Meier survival curve stratified by treatment showing best outcomes for bridge to transplant, followed by bridge to left ventricular assist device (LVAD) and bridge to recovery.

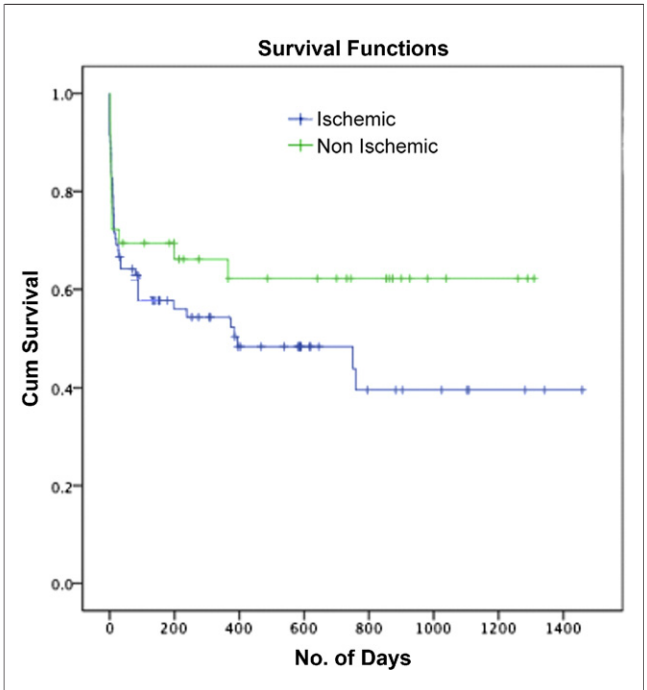

Figure 4 **Survival Analysis Stratified by Ischemic and Nonischemic Cardiomyopathy**

Kaplan-Meier survival curve for ischemic and nonischemic cardiomyopathy showing better survival in nonischemic cardiomyopathy as compared with ischemic cardiomyopathy.

vasopressors after implantation ($p = 0.07$) as compared with the survivors. Survivors showed a significant improvement in pulmonary capillary wedge pressure, lactic acid, and ejection fraction between pre- and post-implantation values as compared with nonsurvivors. In a univariate analysis of baseline parameters and biochemical and hemodynamic parameters before implantation, age, IABP use, and CPR were found to have a statistically significant difference between survivors and nonsurvivors (Tables 5, 6, and 7). In a multivariate analysis of survivors versus nonsurvivors, pre-implantation CPR (hazard ratio 4.54; $p = 0.04$) was the single most important and significant risk factor after

Table 4 **Safety and Efficacy of Use of Tandem Heart Percutaneous Ventricular Assist Device: Complication Rate in Our Center**

Adverse Event	Frequency	%
Groin hematoma	6/117	5.12
Limb ischemia	4/117	3.41
Bleeding around cannula site	34/117	29.05
Femoral artery dissection	1/117	0.85
Atrial perforation	1/117	0.85
Sepsis	35/117	29.9
Coagulopathy	13/117	11.0
Stroke	8/117	6.83
Blood transfusions	70/117	59.8
Gastrointestinal bleed	23/117	19.65

Table 6 Comparison of Survivors and Nonsurvivors

	Survivors			Nonsurvivors		
Value	Pre-pVAD	With pVAD	p Value	Pre-pVAD	With pVAD	p Value
CI, l/(min·m^2)	0.8 (IQR: 0.9)	3.28 (IQR: 0.57)	<0.001	0.21 (IQR: 0.56)	2.52 (IQR: 1.20)	<0.001
SBP, mm Hg	80 (IQR: 15)	105 (IQR: 10)	<0.001	68.0 (IQR: 12)	100 (IQR: 14)	<0.001
DBP, mm Hg	35 (IQR: 15)	70 (IQR: 15)	<0.001	30 (IQR: 10)	60 (IQR: 15)	<0.001
MAP	60 (IQR: 34)	82 (IQR: 12)	0.009	33 (IQR: 20)	80 (IQR: 15)	<0.001
SVO_2, %	49 ± 123	70 ± 15	<0.001	45 ± 12	69.4 ± 11.6	0.008
PCWP, mm Hg	33.71 ± 9.06	16.53 ± 10.35	<0.001	29.06 ± 13.27	21.33 ± 12.22	0.22
PAP, mm Hg	40.82 ± 12.84	27.44 ± 8.30	<0.001	36.07 ± 10.28	24.17 ± 6.94	0.01
Lactic acid, mg/dl	24 ± 36	10 ± 6	<0.001	61 ± 115	16 ± 58	0.053
Cr, mg/dl	1.5 ± 0.9	1.2 ± 0.7	0.015	1.65 ± 1.77	1.4 ± 0.85	0.04
BUN, mg/dl	34.12 ± 17.79	28.43 ± 15.86	0.52	42.22 ± 17.65	31.44 ± 17.0	0.19
Urine output, ml/day	75 ± 60	1,420 ± 1,000	<0.001	73.91 ± 65.6	1,000 ± 650	0.019
EF, %	20 (IQR: 5)	40 (IQR: 20)	<0.001	22 (IQR: 11.5)	28.5 (IQR: 28)	0.064
Hemoglobin	11.8 (IQR: 2.9)	9.9 (IQR: 1.5)	<0.001	10.7 (IQR: 2.8)	10.6 (IQR: 2)	0.692
AST	81.5 (IQR: 297)	48 (IQR: 37.5)	0.120	234 (IQR: 355)	129 (IQR: 580)	0.286
ALT	51 (IQR: 252)	32 (IQR: 62)	0.068	137.5 (IQR: 347)	106 (IQR: 404)	0.591

Cr = creatinine; MAP = mean arterial pressure; PAP = pulmonary artery pressure; other abbreviations in Table 3.

adjusting for age, IABP, MAP, creatinine, and pre-implantation pressors (Table 8).

Discussion

So far, few researchers have evaluated patients with SRCS because of the difficulty in randomizing this extremely high-risk group. Recently, Anderson et al. (17) presented data about the AB5000 (ABIOMED Inc., Danvers, Massachusetts), a surgically placed LVAD used for temporary support in patients with SRCS. Most (87%) of Anderson's patients were receiving IABP and vasopressor support before device implantation, and their baseline hemodynamic values were better than equivalent values in our study. However, the in-hospital (30-day) mortality rate was also

Table 7 Univariate Analysis of Pre-LVAD Values Between Survivors and Nonsurvivors

Parameter	p Value
Age	0.013
pH	0.479
BUN	0.513
PCWP	0.077
Pulmonary arterial pressure	0.195
EF	0.827
Pressors	0.137
Platelets	0.237
Hemoglobin	0.337
D-Dimer	0.550
SVO2	0.95
EF	0.269
Mean arterial pressure	0.837
Cardiac index	0.437
Urine output	0.161
Creatinine	0.259
Hemoglobin	0.236
LDH	0.4
AST	0.014
ALT	0.03
Lactic acid	0.136

Abbreviations as in Table 3.

Table 5 Differences in Baseline Parameters Between Survivors and Nonsurvivors

Parameters	Survivors	Nonsurvivors	p Value
Age, yrs	52.33 ± 15.6	59.32 ± 14.47	0.013
pVAD flow rate	3.39 ± 0.63	3.12 ± 0.86	0.262
ICM	41/64 (64%)	40/53 (75%)	0.229
NICM	23/64 (35.9%)	13/53 (24.5%)	0.299
Male	41/64 (64%)	40/53 (75.5%)	0.229
IABP	48/75 (75%)	48/53 (90.6%)	0.032
CPR	20/64 (31.3%)	36/53 (67.9%)	<0.001
Mechanical ventilation	32/64 (50%)	21/53 (39.6%)	0.448
Pacemaker	23/64 (35.9%)	16/53 (31%)	0.69
Pressors before pVAD placement	1.9 ± 1.24	2.3 ± 1.28	0.136
Pressors after pVAD placement	1.25 ± 1	1.58 ± 1.12	0.07
Groin complications	7/64 (10.9%)	4/53 (7.5%)	0.75
SIRS	16/64 (25%)	19/53 (36.8%)	0.22
Stroke after LVAD	2/64 (3.125%)	6/53 (11.3%)	0.14
Diabetes	22/64 (34%)	17/53 (32.1%)	0.9
Hypertension	30/64 (47%)	35/53 (66%)	0.038
Hyperlipidemia	21/64 (32.8%)	23/53 (43.39%)	0.25
Peripheral vascular disease	8/64 (12.5%)	9/53 (16.9%)	0.39
Stroke before LVAD	5/64 (7.8%)	5/53 (9.4%)	0.49
Atrial fibrillation	11/64 (17.2%)	4/53 (7.5%)	0.167
Chronic kidney disease	25/64 (39%)	22/53 (41.5%)	0.84
Obstructive sleep apnea	8/64 (12.5%)	5/53 (9.4%)	0.76
Smoking	31/64 (48.4%)	14/53 (26.5%)	0.65
Alcohol	11/64 (17.2%)	6/53 (11.3%)	0.41
Drug abuse	2/64 (2.1%)	1/53 (2.0%)	0.9

CPR = cardiopulmonary resuscitation; IABP = intra-aortic balloon pump; ICD = ischemic cardiomyopathy; LVAD = left ventricular assist device; NICM = nonischemic cardiomyopathy; pVAD = percutaneous ventricular assist device.

Table 8 Multivariate Analysis of Survivors and Nonsurvivors

	Hazard Ratio	95% CI	p Value
Age	1.035	0.995–1.076	0.085
IABP	1.028	0.20–5.24	0.974
CPR	4.54	1.61–14.28	0.004
Pressors	1.14	0.76–1.71	0.513
MAP	1.00	0.97–1.02	0.985
Creatinine	1.35	0.86–2.12	0.192

CI = confidence interval; MAP = mean arterial pressure; other abbreviations as in Table 5.

higher in Anderson's patients than in ours (54% vs. 40.2%). Studies evaluating cardiopulmonary support for patients with SRCS have had a high (67%) 30-day mortality rate, as well as a high rate of severe vascular complications (18,19).

Although the SHOCK (Early Revascularization in Acute Myocardial Infarction Complicated by Cardiogenic Shock) trial did not study patients with SRCS, it was the largest and most influential randomized trial to date that has evaluated patients in cardiogenic shock. In comparison with patients in the SHOCK trial, our patients had a lower 30-day in-hospital mortality rate (40.2 % vs. 47%), despite the fact that they presented with SRCS (20). Our ICM patients had worse baseline hemodynamic values than patients in the SHOCK trial: a lower left ventricular ejection fraction (23.43 ± 11.52% vs. 29.1 ± 10.6%), a lower cardiac index (0.36 ± 0.7 l/[min·m^2] vs. 1.8 ± 0.7 l/[min·m^2]), a lower systolic blood pressure (70.9 ± 10.9 mm Hg vs. 89.0 ± 22.8 mm Hg), and a higher pulmonary capillary wedge pressure (29.8± 10.27 mm Hg vs. 24 ± 7 mm Hg), yet they had a lower 30-day mortality (20). In addition, 51.2% of our ICM patients were undergoing resuscitation at the time of pVAD placement, and 43% of this group survived to 30 days. Moreover, our ICM patients had a higher incidence of previous myocardial infarction (80% vs. 40%), previous revascularization (80% vs. 17%), and underlying renal insufficiency (50% vs. 11%) (20).

Compared with the medically treated patients in the SHOCK trial (30-day mortality, 56%), our ICM patients who received a pVAD and were not considered suitable candidates for subsequent revascularization or LVAD implantation had a 30-day mortality rate of 100% (20). This difference in mortality further illustrates how critically ill our patients were. The significant mortality rates of patients in both studies who were treated only with medical therapy emphasizes the need for subsequent revascularization or LVAD placement to significantly improve the survival of ICM patients who present in cardiogenic shock; this finding is consistent with observational data from the SHOCK trial registry and the National Registry of Myocardial Infarction-2 (8,21,22). By providing hemodynamic support, the pVAD enabled ICM patients with SRCS to be bridged to definitive treatment. Despite the delay in revascularization because of persistent shock, the ICM patients who underwent revascularization after pVAD placement had a 50% mortality rate at 6 months, similar to that of their SHOCK trial counterparts (8,23,24).

The pVAD was also effective in providing hemodynamic support to our NICM patients with SRCS. Like the ICM group, these patients had worse baseline hemodynamic values despite IABP and pressor support. The relatively lower in-hospital mortality seen in the NICM group (32% at 30 days) likely reflects both the younger age of these patients relative to the ICM group (41.1 ± 14.8 years vs. 61.8 ± 11.0 years, $p < 0.001$) and the lower incidence of underlying comorbidities.

Previous reports have shown the usefulness of the TandemHeart in stabilizing patients with cardiogenic shock. We have reported earlier our initial experience with the TandemHeart pVAD in 11 patients with ICM or NICM and cardiogenic shock with an initial cardiac index of 1.57 ± 0.3 l/(min·m^2) (25). Thiele et al. (16) reported an initial cardiac index of 1.7 ± 0.3 l/(min·m^2) in their experience with the TandemHeart in 18 consecutive patients who experienced cardiogenic shock after an acute myocardial infarction. Compared with Thiele's group, our ICM group was sicker and subsequently had a higher mortality rate (50% vs. 43%) (16,25).

In our analysis of survivors versus nonsurvivors, the cause of death was either superimposed infection or irreversible end-organ damage and subsequent multisystem organ failure. Of the 21 patients who did not receive an IABP before pVAD placement, 15 (71%; 9 ICM and 6 NICM) were alive at 6 months despite undergoing CPR at the time of device placement. Twenty-four of the 56 patients (43%) with SRCS who underwent pVAD placement while undergoing active CPR survived for at least 30 days; this fact illustrates the efficacy of the pVAD in reestablishing end-organ perfusion and again suggests that earlier placement might have further decreased the total mortality rate.

Early in our experience with the pVAD, 1 device-related death resulted from wire-mediated left atrial perforation. In comparison with previous pVAD series by Thiele et al. (16), ours had a lower incidence of blood loss requiring transfusion (71 of 117 [60%] vs. 19 f 21 [91%]) and a lower incidence of device-related limb ischemia (4 of 117 [3.4%] vs. 7 of 21 [33%]) (26). The low rate of limb complications may be due to routine use of peripheral angiography before cannula selection in our study, and a low threshold for placing an additional ante grade cannula for distal perfusion of the limb (16,26). The relatively higher incidence of bacteremia could be influenced by the large number of patients who received the device after CPR wherein optimal sterile conditions did not exist during emergent line placement, as well as the high number of peripheral catheters associated with monitoring these patients.

Conclusions

The spectrum of cardiogenic shock ranges from moderate hypoperfusion to terminal circulatory collapse and is asso-

ciated with considerable mortality. Although IABP counterpulsation may provide adequate support for moderate cardiogenic shock, more severe shock has traditionally required surgically implanted devices associated with significant death and morbidity. However, in high-risk patients, the pVAD now bridges that gap and provides an additional means of hemodynamic support. The TandemHeart is an effective treatment option for rapidly reversing terminal circulatory collapse and is associated with less device-associated morbidity and mortality. Further prospective randomized trials are warranted to evaluate the efficacy of early pVAD placement in SRCS patients, though these are very difficult to conduct in patients with cardiogenic shock. A more thorough understanding of the full spectrum of cardiogenic shock is needed to tailor therapy and improve outcomes.

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REFERENCES

1. Goldberg RJ, Samad NA, Yarzebski J, Gurwitz J, Bigelow C, Gore JM. Temporal trends in cardiogenic shock complicating acute myocardial infarction. N Engl J Med 1999;340:1162–8.
2. Holmes DR Jr., Bates ER, Kleiman NS, et al. Contemporary reperfusion therapy for cardiogenic shock: the GUSTO-I trial experience. The GUSTO-I Investigators. J Am Coll Cardiol 1995;26:668–74.
3. Holmes DR Jr., Berger PB, Hochman JS, et al. Cardiogenic shock in patients with acute ischemic syndromes with and without ST-segment elevation. Circulation 1999;100:2067–73.
4. Hands ME, Rutherford JD, Muller JE, et al. The in-hospital development of cardiogenic shock after myocardial infarction: incidence, predictors of occurrence, outcome and prognostic factors. The MILIS Study Group. J Am Coll Cardiol 1989;14:40–8.
5. Menon V, White H, LeJemtel T, Webb JG, Sleeper LA, Hochman JS. The clinical profile of patients with suspected cardiogenic shock due to predominant left ventricular failure: a report from the SHOCK Trial Registry. J Am Coll Cardiol 2000;36 Suppl A:1071–6.
6. Rosenbaum AM, Murali S, Uretsky BF. Intra-aortic balloon counterpulsation as a 'bridge' to cardiac transplantation. Effects in nonischemic and ischemic cardiomyopathy. Chest 1994;106:1683–8.
7. Pae WE Jr., Pierce WS. Temporary left ventricular assistance in acute myocardial infarction and cardiogenic shock: rationale and criteria for utilization. Chest 1981;79:692–5.
8. Sanborn TA, Sleeper LA, Bates ER, et al. Impact of thrombolysis, intra-aortic balloon pump counterpulsation, and their combination in cardiogenic shock complicating acute myocardial infarction: a report from the SHOCK Trial Registry. J Am Coll Cardiol 2000;36 Suppl A:1123–9.
9. Norman JC, Cooley DA, Igo SR, et al. Prognostic indices for survival during postcardiotomy intra-aortic balloon pumping. Methods of scoring and classification, with implications for left ventricular assist device utilization. J Thorac Cardiovasc Surg 1977;74:709–20.
10. Shawl FA, Domanski MJ, Hernandez TJ, Punja S. Emergency percutaneous cardiopulmonary bypass support in cardiogenic shock from acute myocardial infarction. Am J Cardiol 1989;64:967–70.
11. Rodrigus IE, Amsel BJ, Conraads V, De Hert S, Moulijn AC. Emergency ventricular assist device: better survival rates in non-post cardiotomy-related cardiogenic shock. Acta Chir Belg 2001;101:226–31.
12. Dang NC, Topkara VK, Leacche M, John R, Byrne JG, Naka Y. Left ventricular assist device implantation after acute anterior wall myocardial infarction and cardiogenic shock: a two-center study. J Thorac Cardiovasc Surg 2005;130:693–8.
13. Ornato JP, Gonzalez ER, Garnett AR, Levine RL, McClung BK. Effect of cardiopulmonary resuscitation compression rate on end-tidal carbon dioxide concentration and arterial pressure in man. Crit Care Med 1988;16:241–5.
14. Chandra NC, Tsitlik JE, Halperin HR, Guerci AD, Weisfeldt ML. Observations of hemodynamics during human cardiopulmonary resuscitation. Crit Care Med 1990;18:929–34.
15. Yannopoulos D, Aufderheide TP, Gabrielli A, et al. Clinical and hemodynamic comparison of 15:2 and 30:2 compression-to-ventilation ratios for cardiopulmonary resuscitation. Crit Care Med 2006;34:1444–9.
16. Thiele H, Lauer B, Hambrecht R, Boudriot E, Cohen HA, Schuler G. Reversal of cardiogenic shock by percutaneous left atrial-to-femoral arterial bypass assistance. Circulation 2001;104:2917–22.
17. Anderson M, Acker M, Kasirajan V, et al. Mechanical circulatory support improves recovery outcomes in profound cardiogenic shock post acute myocardial infarction: a US multicenter study. Am J Cardiol 2005;96 Suppl:11H.
18. Moore CH, Rubin JM, Schnitzler RN, Canon DS, Arpin D. Experience and directions using cardiopulmonary support in fifty-three consecutive cases. ASAIO Trans 1991;37:M340–2.
19. Wittenmyer BL, Pomerants BJ, Duff SB, Watson WD, Blackford JM. Single hospital experience with emergency cardiopulmonary bypass using the portable CPS (Bard) system. J Extra Corpor Technol 1997;29:73–7.
20. Hochman JS, Sleeper LA, Webb JG, et al. Early revascularization in acute myocardial infarction complicated by cardiogenic shock. SHOCK Investigators. N Engl J Med 1999;341:625–34.
21. Scheidt S, Wilner G, Mueller H, et al. Intra-aortic balloon counterpulsation in cardiogenic shock. Report of a co-operative clinical trial. N Engl J Med 1973;288:979–84.
22. Barron HV, Every NR, Parsons LS, et al. The use of intra-aortic balloon counterpulsation in patients with cardiogenic shock complicating acute myocardial infarction: data from the National Registry of Myocardial Infarction 2. Am Heart J 2001;141:933–9.
23. Hochman JS, Sleeper LA, White HD, et al., SHOCK Investigators. One-year survival following early revascularization for cardiogenic shock. JAMA 2001;285:190–2.
24. Hochman JS, Buller CE, Sleeper LA, et al. Cardiogenic shock complicating acute myocardial infarction—etiologies, management and outcome: a report from the SHOCK Trial Registry. J Am Coll Cardiol 2000;36 Suppl A:1063–70.
25. Kar B, Adkins LE, Civitello AB, et al. Clinical experience with the TandemHeart percutaneous ventricular assist device. Tex Heart Inst J 2006;33:111–5.
26. Thiele H, Sick P, Boudriot E, et al. Randomized comparison of intra-aortic balloon support with a percutaneous left ventricular assist device in patients with revascularized acute myocardial infarction complicated by cardiogenic shock. Eur Heart J 2005;26:1276–83.

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