Reversal of Cardiogenic Shock by Percutaneous Left Atrial–to–Femoral Arterial Bypass Assistance

Holger Thiele, MD; Bernward Lauer, MD; Rainer Hambrecht, MD; Enno Boudriot, MD; Howard A. Cohen, MD; Gerhard Schuler, MD

Background—Recovery of myocardial function after revascularization of acutely occluded coronary arteries may require several days. During this critical time, patients in cardiogenic shock may have low output. A newly developed percutaneous left ventricular assist device (VAD) may offer effective treatment for these patients by providing active circulatory support.

Methods and Results—Between May 2000 and May 2001, VADs were implanted in 18 consecutive patients who had cardiogenic shock after myocardial infarction. The device was connected to the patient’s circulation by insertion of a 21F venous cannula into the left atrium by transseptal puncture; blood was returned to the iliac artery through an arterial cannula. Mean duration of cardiac assistance was 4±3 days. Mean flow of the VAD was 3.2±0.6 L/min. Before support, cardiac index was 1.7±0.3 L/min per m² and improved to 2.4±0.6 L/min per m² (P<0.001). Mean blood pressure increased from 63±8 mm Hg to 80±9 mm Hg (P<0.001). Pulmonary capillary wedge pressure, central venous pressure, and pulmonary artery pressure were reduced from 21±4, 13±4, and 31±8 mm Hg to 14±4, 9±3, and 23±6 mm Hg (all P<0.001), respectively. Overall 30-day mortality rate was 44%.

Conclusions—A newly developed VAD can be rapidly deployed in the catheterization laboratory setting. This device provides up to 4.0 L/min of assisted cardiac output, which may aid to revert cardiogenic shock. The left ventricle is unloaded by diverting blood from the left atrium to the systemic circulation, making recovery more likely after an ischemic event. The influence of this device on long-term prognosis warrants further investigation. (Circulation. 2001; 104:2917-2922.)

Key Words: shock ■ heart-assist device ■ extracorporeal circulation ■ myocardial infarction

Cardiogenic shock develops in 7% to 10% of cases after acute myocardial infarction and remains the most common cause of death in these patients.1,2 Despite aggressive treatment modalities such as fibrinolysis and PTCA, mortality rates of cardiogenic shock remain at an unacceptably high level.1,3,4 Recovery of myocardial performance after successful revascularization of the infarcted vessel may require several days. During this period, many patients have low cardiac output. In the past, intra-aortic balloon pumping (IABP) has been the method of choice for mechanical assistance in these patients. It has been shown that IABP can result in initial hemodynamic stabilization; however, in the majority of studies death was merely delayed.5,6 The main limitation of the IABP is the lack of active cardiac support and the requirement of a certain level of left ventricular function. In many patients with severe depression of left ventricular function or persistent tachyarrhythmias, hemodynamic support and left ventricular unloading derived from IABP is insufficient to reverse cardiogenic shock.

Total circulatory support can be achieved by extracorporeal membrane oxygenation, a method fraught with all the drawbacks of extracorporeal circulation such as activation of cellular elements, the need of an oxygenator, and surgery for implantation. Therefore, in recent years, efforts were made to develop ventricular assist devices (VAD) capable of rendering complete hemodynamic support, which are readily connected to the patient’s circulation by interventional methods without the need for extracorporeal oxygenation and surgical procedures. This study was designed to evaluate the utility of a newly developed percutaneous left VAD (Tandem Heart pVAD, Cardiac Assist Technologies, Inc) for short-term stabilization of patients with cardiogenic shock until recovery of the jeopardized myocardium or as a bridge to definite surgical treatment.

Methods

A clinical trial with a newly developed percutaneous left atrial–femoral arterial VAD was conducted from May 2000 to May 2001 in 18 patients with cardiogenic shock as a result of an acute myocardial infarction. Cardiogenic shock was defined as (1) persistent systolic blood pressure <90 mm Hg or vasopressors required to maintain blood pressure >90 mm Hg in the setting of a normal intravascular
volume; (2) evidence of end-organ failure (e.g., urine output <30 mL/h, cold and/or diaphoretic skin and extremities, altered mental status, serum lactate >2 mmol/L); (3) evidence of elevated left ventricular filling pressures, such as pulmonary congestion or pulmonary capillary wedge pressure (PCWP) >15 mm Hg; (4) cardiac index (CI) of <2.0 L/min per m².

Patients were informed of the experimental nature of the procedure if their mental status permitted, otherwise the procedure was discussed with their relatives. The protocol for this study was approved by the local ethics committee.

Description of the VAD System

The Tandem Heart pVAD is a low-speed centrifugal continuous-flow pump with a low blood surface contact area, resulting in reduced potential for hemolysis and thromboemboli. It is dual chambered with an upper housing and a lower housing assembly. The upper housing provides a conduit for inflow and outflow of blood. The lower housing assembly provides communication with the controller, the means for rotating the impeller of the VAD, and an anticoagulation infusion line integral to the pump to provide a hydrodynamic bearing, cooling of the bearing, and local anticoagulation.

The controller is a microprocessor-based electromechanical drive and infusion system. It is designed to operate on AC current or on internal batteries. The controller generates the signals to drive the VAD, which turns the impeller and serves to infuse the anticoagulant solution. For high reliability and enhanced safety, it is provided with a backup control unit.

Implantation of the Device

After percutaneous puncture of the right femoral vein, a standard Brockenbrough catheter was inserted into the superior vena cava; with the use of a modified Ross needle, the interatrial septum was punctured in the fossa ovalis. The position of the Brockenbrough catheter within the left atrium was documented by manual dye injection. If the position was deemed satisfactory, the Brockenbrough catheter was exchanged for a stiff guide wire with a distal soft wire loop identical to the device used for mitral valvuloplasty by the Inoue method (Toray Europe Ltd). The transseptal puncture site was then dilated to 21F with a 2-stage dilator followed by insertion of a venous inflow cannula, which was sutured to the skin of the thigh and cross-clamped. This cannula is made of polyurethane, with a large end hole and 14 side holes to facilitate aspiration of oxygenated blood from the left atrium. An arterial perfusion catheter of 14F to 19F was inserted percutaneously into the right femoral artery or two arterial perfusion catheters of 12F into both femoral arteries and then

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**TABLE 1. Patient Characteristics and Outcomes**

<table>
<thead>
<tr>
<th>Patient No.</th>
<th>Age, y/Sex</th>
<th>Cause of Shock</th>
<th>Extent of CAD</th>
<th>IRA</th>
<th>Adjunctive PTCA/Stent</th>
<th>EF, %</th>
<th>Arterial Cannula (French)</th>
<th>Mean Flow, L/min</th>
<th>Days Supported</th>
<th>Complications</th>
<th>Additional Procedure</th>
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<tr>
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<td>LM</td>
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<td>24</td>
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<td>CABG</td>
</tr>
<tr>
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<td>3</td>
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<td>2</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
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<td>RCA</td>
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<td>3</td>
<td>Dislocation arterial cannula</td>
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<td>17</td>
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<tr>
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<tr>
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<tr>
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<td>4</td>
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<td>LAD</td>
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<td>LAD</td>
<td>Yes</td>
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<td>17</td>
<td>3.6</td>
<td>4</td>
<td>Limb ischemia</td>
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</table>

CAD indicates coronary artery disease; IRA, infarct-related artery; EF, ejection fraction; AMI, acute myocardial infarction; VSD, ventricular septal defect; LM, left main; RCA, right coronary artery; LAD, left anterior descending coronary artery; and MODS, multiorgan dysfunction syndrome.
advanced into the lower abdominal aorta. Heparin-coated Tygon tubing with a total length of 30 cm was used for connection to the device after carefully deairing according to standard techniques (Figure 1). The pump was activated at low speed, and all air bubbles were removed through a 3-way stopcock inserted into the arterial line next to the pump. When all lines were completely air free, the arterial clamp was removed and the pump speed increased to maximum (7500 rpm). Flow through the arterial line was measured by an electromagnetic flowmeter (HT 311, Transonic). Heparin was administered continuously through the lubrication system of the device, and the activated clotting time was maintained at \( \approx 200 \) seconds by adjusting the amount of added heparin.

**Hemodynamic Monitoring**

Hemodynamic data were acquired before and after implantation of the VAD. On the following days, measurements were obtained daily with “pump off” and “pump on.” For “pump on,” the VAD was operated at full speed (7500 rpm); for “pump off,” the speed of the pump was reduced to 3000 rpm and the arterial cannula was clamped. Because of the danger of clotting, the pump must not be switched off completely. The following parameters were measured: cardiac output, CI, blood pressure, pulmonary artery pressure, PCWP, central venous pressure, and heart rate. For quantification of ventricular left-to-right shunts in patients with infarct-related ventricular septal defect (VSD), shunt volume, shunt-flow ratio, and effective cardiac output were determined by the Fick method. Additionally, standard base excess, serum lactate, and pH were determined with the use of a commercially available Astrup System.

**Weaning and Explantation of the Device**

Those patients who did not undergo emergency CABG or VSD closure were weaned from the VAD if no more inotropic drugs were required and the hemodynamic parameters remained stable. A stepwise reduction of the pump output in steps of 500 mL/min was performed according to the hemodynamic stability of the patient. Further reduction was performed after approximately 1 to 2 hours, resulting in a weaning procedure of 6 to 12 hours in most patients. After weaning, the venous and arterial cannula were removed by surgical approach.

**Statistical Analysis**

Each categoric factor is described as the number and the percentage of patients. For continuous parameters, mean±SD values are given. After testing of the assumption that the differences are sampled from a gaussian distribution, results were compared by a paired \( t \) test for preimplantation and postimplantation and “pump on” and “pump off” status. Continuous parameters not sampled from a gaussian distribution were compared by the nonparametric Wilcoxon rank-sum test with the use of statistical software (SigmaStat 2.03, Version 2.0, SPSS Inc). A value of \( P<0.05 \) was considered statistically significant.

**Results**

**Patient Characteristics**

A total of 18 patients (12 men and 6 women) were enrolled in this study. Mean age was 63±12 (range, 44 to 89) years. At the time of enrollment, all patients were in cardiogenic shock according to the criteria previously defined. The underlying cause was acute myocardial infarction in all patients; in 5 patients, a ventricular septal defect had been diagnosed within 1 to 3 days after the acute myocardial infarction. Mean duration of cardiac support was 4±3 days. Further patient characteristics, clinical course, and outcome are described in Table 1.

**Hemodynamic Characteristics**

Hemodynamic indexes before and after implantation of Tandem Heart pVAD are shown in Table 2. Hemodynamic data after implantation were collected during the first 2 hours after transfer from the catheterization laboratory to the intensive care unit. Hemodynamic parameters were improved in all patients after implantation of the VAD (Figure 2). Metabolic acidosis and serum lactate could be reversed (Figure 3). CI, mean blood pressure, PCWP (Figure 4), and all other hemodynamic parameters were improved with the active Tandem Heart pVAD system compared with the “pump off” status during the duration of support. In patients with infarct-related VSD, the left-to-right-shunt volume was reduced from 4.5±0.8 L/min to 2.0±1.0 L/min; the shunt flow ratio was reduced from 2.6±0.4 to 1.6±0.2; and the effective CI was increased from 1.4±0.3 to 2.0±0.4 L/min per m² by the VAD.

The mean flow of the VAD was 3.3±0.6 L/min. The device can be operated at various speeds, which can be continuously adjusted from 3000 rpm to 7500 rpm. Under optimal conditions, with the use of a large arterial cannula, up to 4 L/min can be provided at 7500 rpm and nearly 0 L/min at 3000 rpm. During operation at maximum output, pulsatile blood flow is reduced substantially and is partially replaced by nonpulsatile flow. Transesophageal echocardiographic examinations performed during operation of the device showed that blood flow in the aorta was reversed up to the level of the aortic arch.

**Clinical Course and Outcome**

The implantation procedure was uneventful in all patients. Hemolysis remained negligible, as monitored by plasma-free hemoglobin and haptoglobin. During the follow-up period, 5 patients required transfusions of packed red blood cells as the
result of bleeding at the arterial access site. After compression with a femoral compression system (Femostop II Plus, Radi Medical Systems) and a mild reduction of the heparin dose, bleeding was stopped. In two patients with peripheral arterial occlusive disease, ischemia of the right lower limb developed some hours after implantation of a 17F arterial cannula. Limb ischemia was resolved in both by surgical implantation of an accessory antegrade cannula into the right common femoral artery.

During support, there were 4 patient deaths. One of these patients was extremely overweight (130 kg). This patient was hemodynamically stable until a standard length arterial cannula of 6.5 cm (Fem-Flex II, Baxter Deutschland GmbH) dislodged during daily routine nursing care. He immediately had profound arterial hypotension and died in cardiogenic shock before the problem could be resolved. To minimize the danger of dislodgment, an 18-cm-long arterial cannula (Bio-Medicus, Medtronic, Inc) was used in subsequent patients.

The second patient had an ischemic stroke 24 hours after initiation of the extracorporeal support. This patient had an infarct-related VSD before the use of the VAD. Computer tomography of the brain showed multiple small infarctions. The patient died 6 days later of bacterial peritonitis, which was caused by a colon perforation after manipulation with a rectal cannula, which was used to treat severe diarrhea. At autopsy, disseminated cerebral infarctions were detected, most likely as the result of multiple cerebral emboli. The edge of the large VSD, measuring 4 × 2 cm, was surrounded by a large thrombus. In addition, smaller thrombi had formed at the left atrial puncture site despite the continuous use of anticoagulation drugs.

The third patient had a proximal occlusion of the right coronary artery (RCA). This patient had right ventricular failure. Her right atrial pressures approached pulmonary artery pressures, thus resulting in insufficient support by the VAD. The fourth patient had an infarct-related VSD. This patient died as a result of a sudden deterioration of the VSD. The autopsy revealed a VSD of 6 × 2 cm, which probably led to right ventricular overload.

Four more patients died after weaning from the Tandem Heart pVAD: Two died of recurrent cardiogenic shock, one died during surgery, and one on a long-term VAD died after successful surgical closure of a VSD. The remaining 10 patients were discharged and remained alive 30 days after support. Overall 30-day mortality rate was 44% (Table 1).

**Discussion**

In patients with acute myocardial infarction, hemodynamic failure is the most frequent cause of in-hospital death. In the present study, an initial experience with a newly developed percutaneous VAD has shown that complete hemodynamic support can be instituted within 30 minutes in these patients.
Pulmonary edema and metabolic derangements associated with cardiogenic shock disappear within hours even in patients with profound depression of left ventricular performance. The use of the left VAD provides a crucial time window for revascularization of the infarcted vessel and recovery of myocardial contractility.

The implantation procedure is straightforward, relying on standard heart catheter techniques such as transseptal puncture without the need for surgical exposure of vascular access. The key part is a centrifugal pump, which is capable of supplying sufficient support independent of residual left ventricular performance. This feature is not provided by the IABP. Hemodynamic assessments before and after implantation were significantly improved during the use of the device. In addition, cardiogenic shock was reversed in all but one patient with right ventricular failure, which is deemed a contraindication when the right ventricular failure is predominant. In this patient, insufficient blood was supplied to the device as the result of low left atrial pressures rendering the pump ineffective.

Several problems have been encountered during the initial clinical operation of this device, including the dislodgment of a standard-length arterial cannula of 6.5 cm in an overweight patient and the sudden loss of hemodynamic support during the daily nursing care of the patient. These problems were resolved by using an extra-long arterial cannula (18 cm in length) in subsequent patients.

In this study, one patient had thrombi at the edge of a large VSD and to a lesser extent at the atrial puncture site despite adequate anticoagulation with heparin. This event resulted in cerebral emboli, which may have been caused by a state of hypercoagulability secondary to cardiogenic shock.

Two patients with peripheral occlusive artery disease had distal limb ischemia, probably caused by the use of the 17F arterial cannula. To minimize ischemic problems in patients with small pelvic arteries and in patients with arterial occlusive disease, visualization of the vessels by dye injection before insertion of the cannula may be prudent.

A VSD is deemed to be a relative contraindication for left atrial-to-femoral arterial bypass support because of the risk of right-to-left shunting with subsequent hypoxemia. However, our experiences could show that by careful hemodynamic monitoring, unloading of the left ventricle is never complete and therefore no right-to-left shunt could be detected. The VAD reversed cardiogenic shock in patients with a VSD, which allowed bridging to surgical repair.

Currently, little is known about the fate of the transseptal puncture site after removal of the 21F venous cannula. In patients undergoing mitral valvuloplasty by Inoue balloon, a left-to-right shunt can be detected in the majority of patients. However, it decreases or disappears completely after 6
months, with no significant effect on hemodynamic parameters. In previous animal studies, the atrial septal defects induced by left atrial cannulation during the use of a VAD have been shown to heal completely at the end of 4 to 6 weeks or result in a clinically insignificant left-to-right shunt. This hypothesis was confirmed by the absence of a relevant left-to-right shunt after weaning the patients from the VAD.

Previous Left Atrial–to–Femoral Arterial Bypass Support
In 1962, Dennis et al were the first to describe the left atrial–to–femoral bypass system by the jugular approach. Consecutively, left atrial–to–femoral arterial VAD were mostly used in patients who could not be weaned from cardiopulmonary bypass after cardiothoracic surgery. Currently, there are only few reports of totally percutaneous approaches in which the VAD was implanted in the catheterization laboratory setting for patients undergoing high-risk interventions with a mean operating time of 43 minutes or in two patients for cardiogenic shock. However, until now, this technique has not achieved widespread popularity as a circulatory support because of the lack of a transseptal cannula that can accommodate the flow rates necessary to provide adequate circulatory support for long-term clinical use. Furthermore, the pumps used so far were operated at a higher speed and were not provided with an additional housing assembly, which allows the high local concentration of anticoagulant within the pump and avoids warming up. Both are of paramount importance to avoid thrombus formation at the impeller and to substantially reduce the inherent hemolysis of centrifugal pumps.

Effects of Left Atrial–to–Femoral Arterial Bypass
Recovery of the myocardium after revascularization occurs by diverting blood from the left atrium to the systemic circulation, which will result in reducing filling pressure in the left ventricle, cardiac workload, and oxygen demand. Previous animal studies have demonstrated a substantial decrease in the size of acute myocardial infarction by use of these left VADs with or without recanalization of the infarct related artery. Furthermore, left atrial–to–femoral arterial support results in an increased systemic blood pressure, which may favorably affect the imbalance between oxygen demand and supply of the jeopardized myocardium and may lead to optimal tissue perfusion. However, little is known about the effects of a continuous flow in contrast to a pulsatile flow in coronary arteries.

Study Limitations
This major limitation of this prospective cohort study is the lack of a control group. The small number of patients does not allow matching with other patient groups, although considering the low mortality rate of 31% in patients without a VSD, which also includes our initial learning curve, the results are promising in comparison to the mean 60% mortality rate in the Shock Trial Registry.

Conclusions
The systemic circulation of patients with cardiogenic shock can be substantially improved by using a newly developed percutaneous left atrial–to–femoral arterial VAD. This device may aid to reverse cardiogenic shock by unloading the left ventricle and allowing the recovery of the myocardium after an ischemic event. The influence of this device on long-term prognosis warrants further investigation.

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References
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