First Clinical Experience With the DeBakey VAD Continuous-Axial-Flow Pump for Bridge to Transplantation

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Background—A shortage of donor organs and increased numbers of deaths of patients on the waiting list for cardiac transplantation make mechanical circulatory support for a bridge to transplantation a standard clinical procedure. Continuous-flow rotary blood pumps offer exciting new perspectives.

Methods and Results—Two male patients (ages 44 and 65 years) suffering from end-stage left heart failure were implanted with a DeBakey VAD axial-flow pump for use as a bridge to transplant. In the initial postoperative period, the mean pump flow was 3.9±0.5 L/min, which equals a mean cardiac index (CI) of 2.3±0.2 L · min⁻¹ · m⁻². In both patients, the early postoperative phase was characterized by a completely nonpulsatile flow profile. However, with the recovery of heart function 8 to 12 days after implantation, increasing pulse pressures became evident, and net flow rose to 4.5±0.6 L/min, causing an increase of mean CI up to 2.7±0.2 L · min⁻¹ · m⁻². Patients were mobilized and put through regular physical training. Hemolysis stayed in the physiological range and increased only slightly from 2.1±0.8 mg/dL before surgery to 3.3±1.8 mg/dL 6 weeks after implantation.

Conclusions—The first clinical implants of the DeBakey VAD axial-flow pump have demonstrated the device to be a promising measure of bridge-to-transplant mechanical support. (Circulation. 2000;101:356-359.)

Key Words: heart failure ■ heart-assist device ■ DeBakey VAD

A shortage of suitable donor grafts prolongs the waiting time for cardiac transplantation and increases the number of patients who die while on the waiting list. Bridge-to-transplant programs with mechanical assist devices were successfully installed to overcome the problem of acute hemodynamic deterioration in patients on the waiting list. Development of technically reliable pulsatile mechanical assist devices over the past 3 decades guarantees their feasibility for long-term bridge-to-transplantation support up to 2 years. However, device size and noise and infection of the power/vent line limit the use of these devices. Axial-flow impeller pumps, with their potential for small size, low noise, and absence of a compliance chamber, have been developed for clinical use during the past 10 years. Of 4 potential candidates (Jarvik 2000 Heart,1 DeBakey VAD,2 Nimbus/Pittsburgh axial-flow blood pump,3 and Sun Medical/HiJ/Waseda/Pittsburgh intraventricular axial-flow blood pump4), the DeBakey VAD was the first clinically used. We report the first successful clinical implants of the continuous-flow DeBakey VAD for bridge to transplant in 2 patients in our institution.

Methods

DeBakey VAD
The electromagnetically actuated DeBakey VAD is a miniaturized, fully implantable titanium axial-flow blood pump (Figure 1). A titanium inflow cannula connects the pump to the apex of the left ventricle, and a Vascutec Gelweave vascular graft as an outflow conduit connects the pump to the ascending aorta. An ultrasonic flow probe is placed around the outflow conduit. Together with the flow probe’s wiring, the pump motor cable exits the skin superior to the probe’s wiring. The measured pump flow is displayed either on the external VAD controller or when connected on the clinical data acquisition system (CDAS) together with pump speed, power consumption, and current signals from the pump. Adjustments to the pump speed can be performed only when it is connected to the CDAS. For optimal mobilization of the patient and freedom to move, power can be delivered by two 12-V DC batteries for several hours.

Patients
Two male patients suffering from end-stage left heart failure received a DeBakey VAD as a left ventricular assist device for bridge to transplantation (Table 1). Both patients were listed for cardiac transplantation and showed signs of acute hemodynamic deteriora-
tion and end-organ dysfunction at the time of implantation. These 2 patients were the first in our center to enroll in a multi-institutional study in Europe. The protocol for the study was approved by the Institutional Review Committee, and both patients provided written informed consent.

Operation
Like other left ventricular assist devices, this pump is implanted through a median sternotomy with extracorporeal circulation (ECC). The pump was placed in a small, left-sided extracardiac pocket. A sewing ring was attached to the apex of the beating heart with circumferentially placed buttressed sutures. An inflow cannula was inserted into the ventricle, and a Dacron skirt of the cannula was sutured to the apical ring. The Vascutec outflow graft was placed extrapericardially and anastomosed to the ascending aorta. The VAD was easily deaired, and the pump was started while ECC was gradually discontinued. A combined cardiac and pump output was maintained at a cardiac index of $2.0 \text{ L} \cdot \text{min}^{-1} \cdot \text{m}^{-2}$ obtained with a Swan-Ganz catheter.

Anticoagulation
The study protocol allowed individual anticoagulation regimens according to each center’s previous device experience. During ECC and implantation of the pump, the patient received heparin 300 U/kg body wt IV, and the heart-lung machine was primed with 1 000 000 IU aprotinin. After discontinuation of ECC, heparin was reversed with an appropriate dose of protamine. Intravenous heparin was instituted 6 hours after surgery to achieve activated partial thromboplastin target times of 50 to 60 seconds. Platelet antiaggregation therapy with 150 mg/d aspirin and 225 mg/d dipyridamole was started after removal of all chest drains. Administration of heparin was stopped when anticoagulation with coumarin reached target levels of INR 2.5 to 3.5.

Statistical Analysis
All results for continuous variables are expressed as mean±SD. Students paired or unpaired $t$ test, if appropriate, was used to compare continuous variables between 2 subgroups. A value of $P<0.05$ was considered indicative of statistical significance.

Results
Clinical Course
The intraoperative course in both patients was uneventful, and the pump showed good performance, with flow rates of 3 to 5 L/min after gradual discontinuation of ECC, and adequate tissue perfusion was achieved with mixed venous oxygen saturation >60%. However, full unloading of the extremely enlarged ventricles in this early period could not be achieved, but transesophageal echocardiography showed a closed aortic valve, and no pulsations in the aortic blood pressure curve could be detected. Pump flow increased within the first days after surgery and stabilized at flow rates of $4.5 \pm 1.2 \text{ L} \cdot \text{min}^{-1}$ after postoperative week 3 (Figure 2). Because the aortic valve stayed closed all the time (as shown by echocardiography), we calculated a cardiac index of $2.7 \pm 0.2 \text{ L} \cdot \text{min}^{-1} \cdot \text{m}^{-2}$. After initial early extubation, both patients needed surgical reinterventions on postoperative days 5 and 6, respectively. Anticoagulation overtreatment caused bleeding in patient 1; patient 2 presented a laceration of the subclavian vein caused by catheter insertion. Subsequently, both patients were mobilized, and inotropic support for sufficient right heart function could be discontinued. Both patients were moved from the intensive care unit to an intermediate care ward and were put through regular physical training to rebuild the muscle mass lost during prolonged periods of preoperative immobilization.

Hemodynamic Changes
The initial period after implantation of the DeBakey VAD was characterized by complete nonpulsatile arterial blood pressure in both patients. Despite the aortic valve staying closed, the pump was started with a low cardiac output of $2.0 \text{ L} \cdot \text{min}^{-1} \cdot \text{m}^{-2}$. A combined cardiac and pump output was maintained at a cardiac index of $2.0 \text{ L} \cdot \text{min}^{-1} \cdot \text{m}^{-2}$ obtained with a Swan-Ganz catheter.

| TABLE 1. DeBakey VAD Patient Demographics |
|-------------------------------------------------|-------------------|
| **Age, y/sex**                                  | **Patient 1**     | **Patient 2**     |
| Dilated cardiomyopathy                          | 44/M              | 65/M              |
| Ischemic cardiomyopathy                         |                   |                   |
| Intra-aortic balloon pump                       | No                | No                |
| Ventilation                                     | No                | No                |
| NYHA class                                      | IV                | IV                |
| Aortic pressure, mm Hg                          | 88/54/68          | 105/54/78         |
| Pulmonary artery pressure, mm Hg                | 69/38/48          | 48/25/32          |
| Pulmonary capillary wedge pressure, mm Hg       | 28                | 20                |
| Cardiac index, $\text{L} \cdot \text{min}^{-1} \cdot \text{m}^{-2}$ | 1.8              | 1.9               |
| Pulmonary vascular resistance, dyn · s/cm²     | 514               | 166               |
| Intravenous medication                          | Dobutamine 5 $\mu\text{g} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ | Dopamine 6 $\mu\text{g} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ |
| Prostaglandin E 5 ng · kg⁻¹ · min⁻¹            |                   |                   |
| Milrinone 0.5 $\mu\text{g} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ |                   |                   |
closed, modulation of pulsatility with low amplitude to the nonpulsatile blood flow produced by the VAD could be achieved by varying pump flow. Mean arterial blood pressures were always kept in the range of 70 to 90 mm Hg, and flow rate was adjusted to obtain mixed venous oxygen saturation >60%. After this initial nonpulsatile period, low-amplitude pulsations became more frequent and were associated with recovered left ventricular contractility, but at all times nonpulsatile flow patterns could be produced with an increase in pump speed.

**Device Performance**
In both patients, the DeBakey VAD provided adequate flow to maintain sufficient tissue perfusion expressed by mixed venous oxygen saturation >60% in the early perioperative period. Pump speed was set between 9000 and 11 000 rpm and was adjusted manually in this early phase to avoid excess suction with ventricular collapse, which was easily detected in the pump flow curve. With hemodynamic stabilization of the patients, pump flow increased gradually from 3.9±0.5 L/min in postoperative week 1 up to 4.5±0.6 L/min after postoperative week 3, with peak flows >6 L/min. Sudden pump desynchronizations followed by automatic restarts could be detected in both patients but did not dramatically affect patients in their daily routine. On postoperative day 60, 1 patient encountered an 18-minute, probably connector-related pump stop, which occurred during his daily exercise on the bicycle. The patient tolerated a regurgitation of 1.3 L/min through the pump, although he needed short-term intravenous inotropic support. He recovered immediately when the pump was successfully restarted and provided flows of >5 L/min.

**Hemolysis**
Table 2 shows indices of hemolysis for both patients before surgery and at 1, 2, 3, 4, 5, and 6 weeks after implantation. No statistically significant elevation of mean plasma-free hemoglobin was detected. Serum creatinine levels declined from a slightly elevated preoperative level to normal. Lactate dehydrogenase increased significantly during the postoperative period, but only patient 2 developed peak levels of >800 U/L 4 weeks after implantation, together with elevated levels of γ-glutamyl transferase and no correlation with single peaks in plasma-free hemoglobin.

**Discussion**
Pulsatile blood pressure profile was always considered necessary to maintain sufficient tissue perfusion in mammals. Early studies with nonpulsatile blood flow in calves performed by Johnston et al in 1976 gave the first evidence of

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**Figure 2.** Pump flow, pump speed, and pump motor current for DeBakey VAD axial-flow pump in patient 1.

**Table 2.** Indices of Hemolysis

<table>
<thead>
<tr>
<th></th>
<th>Before Surgery</th>
<th>1 Week</th>
<th>2 Weeks</th>
<th>3 Weeks</th>
<th>4 Weeks</th>
<th>5 Weeks</th>
<th>6 Weeks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hb, g/dL</td>
<td>11.5±0.4</td>
<td>10.3±1.0</td>
<td>9.9±0.8</td>
<td>10.3±0.6</td>
<td>10.7±0.7</td>
<td>12.0±0.5</td>
<td>12.2±1.1</td>
</tr>
<tr>
<td>fHb, mg/dL</td>
<td>2.1±0.8</td>
<td>3.2±3.4</td>
<td>3.3±1.8</td>
<td>3.4±1.3</td>
<td>6.5±4.1</td>
<td>2.9±1.2</td>
<td>3.3±1.8</td>
</tr>
<tr>
<td>LDH, U/L</td>
<td>156±7</td>
<td>335±103*</td>
<td>375±58*</td>
<td>473±93*</td>
<td>595±224*</td>
<td>517±158*</td>
<td>442±115*</td>
</tr>
<tr>
<td>Crea (mg/100 ml)</td>
<td>1.18±0.5</td>
<td>1.0±0.2</td>
<td>0.94±0.1</td>
<td>0.87±0.2</td>
<td>0.9±0.1</td>
<td>0.94±0.1</td>
<td>0.89±0.2</td>
</tr>
</tbody>
</table>

Hb indicates hemoglobin; fHb, plasma free hemoglobin; LDH, lactate dehydrogenase; and Crea, serum creatinine. Data are mean±SD.

*P<0.05.
tolerance of this nonphysiological blood flow pattern. Later, Golding et al. were able to sustain survival for up to 34 days. Yada and associates supported calves with nonpulsatile blood flows for >3 months but hypothesized a need for an ≈20% higher blood flow than with pulsatile perfusion to avoid transient physiological disorders. In our patients, we could demonstrate for the first time that continuous blood flow, generated by an implanted axial-flow pump, over a period of >60 days is well tolerated in humans. The pumps generated low hemolysis, within physiological ranges. In accordance with the early animal experiments, these first clinical implants provide no evidence of disadvantages of this unphysiological continuous-flow condition in humans. This generates optimism for a more widespread use of implantable rotary blood pumps as long-term mechanical support. In contrast to the electric pusher-plate pumps, axial-flow pumps are silent, are smaller in size, have lower energy requirements, and provide the prospect of low device costs. Nevertheless, a number of questions are as yet unanswered. Some of them are general concerns applicable to all kinds of rotary blood pumps, such as the absence of an inherent Frank-Starling mechanism and its consequences during exercise, as well as the definition of control parameters to optimize pump-speed adjustments and avoid excess suction. Such questions as noninvasive measurement of nonpulsatile or low-pulsatile blood pressures of fully mobilized and exercising patients will have to be addressed in the future. Furthermore, episodes of stalling and consecutive pump stops and restarts have not yet been sufficiently explained. Other questions involve construction specifications of the pump, such as the geometry and diameter of the pump inflow cannulas.

In conclusion, the first clinical implants of the DeBakey VAD axial-flow pump have demonstrated the feasibility of continuous-blood-flow pumps as a promising measure of bridge-to-transplant mechanical support. This new technology opens exciting possibilities with evident advantages, but a number of questions remain open with regard to use of the pumps in humans.

Acknowledgment

The DeBakey VAD devices were provided according to an Ethics Committee–approved study protocol by MicroMed Technology Inc.

References

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