Mechanical support of the circulation followed by cardiac transplantation

Improvements in both mechanical circulatory support devices and immune therapy promise a wider use of sequential mechanical support as a bridge to orthotopic cardiac transplantation. The intra-aortic balloon pump, the left and right ventricular assist pumps, and the pneumatic artificial heart represent the range of devices capable of keeping a patient alive who is awaiting a donor organ. The major difficulty in using circulatory support devices is infection, which is caused by their required percutaneous tubes. We report here our experiences with mechanical circulatory support devices as a bridge to cardiac transplantation.

In a series of 31 consecutive transplant procedures, six patients have required preoperative mechanical circulatory support. The intra-aortic balloon pump was used in two patients for 2 and 14 days, respectively, before transplantation. Both patients are well 10 and 11 months after the transplant procedure. Two patients required the left ventricular assist device for 11 and 21 days and are alive 3 weeks and 8 months, respectively, after transplantation. One patient was supported by the pneumatic artificial heart for 10 days before a donor heart became available but died of septic shock 17 days after transplantation. A second patient received a pneumatic artificial heart 7 days after transplantation when the heart transplant failed. He has been in stable condition for 45 days but is recovering from renal failure.

Our early experiences indicate that either partial or total mechanical support as a bridge to transplantation is successful if overwhelming sepsis or renal failure can be avoided.

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The intra-aortic balloon, left ventricular assist device, and pneumatic artificial heart have each been used to support the circulation in patients before cardiac transplantation. Reemstma and associates,1 at the Columbia Presbyterian Medical Center, were the first to report the use of the intra-aortic balloon pump before orthotopic cardiac transplantation. Their patient was in acute cardiogenic shock. Bregman and his colleagues2 reported on six patients who underwent cardiac transplantation after intra-aortic balloon pump support. All but one survived the immediate postoperative period.

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Staged cardiac transplantation, with either a left ventricular assist device or a total artificial heart, has been performed by Cooley3 in three patients. All three survived the first stage and then received an allograft 39 hours, 64 hours, and five days, respectively, after the device was implanted. The allograft then sustained circulation for 32 hours, 7.5 days, and 20 days, respectively, before each patient died. Using calves, Olsen,4 Gaykowski,5 and their colleagues at the University of Utah have implanted an artificial heart before cardiac transplantation. In eight experiments, six animals lived from 2 days to several years with an allograft. This experiment demonstrated the technical feasibility of performing cardiac transplantation after several months of total artificial heart support. Because chimeric twin calves were used for these procedures and no immunosuppressive drugs were required postoperatively, these experiments may not be compared to human situations.

The challenge of mechanical support of the circula-
tion before cardiac transplantation does not center around the technique of implantation. Technically more demanding operations are performed daily around the world. It can be generally assumed that the use of mechanical heart replacement followed by cardiac transplantation, utilizing the immune suppressive measurements previous to the discovery of cyclosporine, would in all probability lead to lethal infectious complications. Cyclosporine combined with lower doses of steroids currently used in many transplant programs may provide the required degree of immune suppression but not eradicate the host's resistance to infection and thereby allow survival.

We report here our own experience with mechanical circulatory support devices used as a bridge to cardiac transplantation.

Methods

The current Pennsylvania State University clinical assist device employs a paracorporeal pneumatically powered sac-type blood pump, a pneumatic power unit, and a control unit (Fig. 1). The blood pump sac is made of segmented polyurethane (Biomer, Ethicon, Inc., Somerville, N. J.) and the rigid outer housing is made of polysulfone. Björk-Shiley 60 degree convexo-concave tilting inlet and outlet disc valves (Delrin) are used to provide unidirectional flow. The pumping action is generated by a pneumatic power unit that pulses air between the pump housing and the flexible sac to periodically compress the valved blood sac. The pump has a dynamic stroke volume of 65 ml and a maximum output of 6.5 L/min. The power unit, using a fill switch trigger, activates the blood pump from full stroke, although, when a lesser output is needed, the pump can be activated at a fixed, preset rate. Approval for its clinical use was obtained from our institutional review board in 1976. An Investigational Device Exception for clinical use of the system was obtained from the Food and Drug Administration. The assist device has been used extensively clinically in patients after cardiac operations and cardiogenic shock. In potential recipients of a heart, blood is removed from the ventricular apex through a wire-reinforced large-caliber (13 mm internal diameter) end-hole cannula of segmented polyurethane with outer coverings of Dacron velour. Blood return is achieved through the composite segmented polyurethane-woven Dacron prosthesis anastomosed to the ascending aorta.

The pneumatic artificial heart designed and constructed at The Pennsylvania State University consists of two separate prosthetic ventricles each similar to the ventricular assist device (Fig. 2). The inlet and outlet connectors contain a union nut to attach the prosthetic ventricle to the natural atrial remnant and to the great vessel. Atrial cuffs are made of polymer-coated stretch fabric. Dacron vascular prostheses interface the outlet portion of the ventricles to the great arteries. The blood sac fills with blood and empties by introducing air pulses between it and its rigid housing. Unidirectional blood flow is ensured by the use of Björk-Shiley prosthetic valves (Delrin discs), which have excellent mechanical durability and a favorable ratio of orifice area to cross-sectional area. Its clinical use was approved by our own institutional review board and the Food and Drug Administration in 1985.

The pneumatic power units and the control system are housed in a separate console and supply air pulses to
Fig. 2. The Pennsylvania State pneumatically powered artificial heart.

the artificial heart by way of large-bore percutaneous tubes. The tubes are tunneled subcutaneously. In their transthoracic region, the tubes are covered with velour to encourage tissue ingrowth and to provide firm fixation to the skin and connective tissues to thereby reduce bacterial invasion. Each ventricle is driven by a separate pneumatic power unit that allows independent control of both systolic pressure and diastolic vacuum as well as systolic and diastolic duration. An automatic control system has been developed. Negative feedback loops are used to vary the ventricular rate while arterial and atrial pressures are maintained within a normal range.

Orthotopic cardiac transplantation was performed by the technique described by Lower and Shumway. Donor hearts were perfused with 1,000 ml of crystalloid cardioplegic solution at 4°C before removal, and additional doses of crystalloid cardioplegic solution were given during transplantation. Immunosuppressive therapy was administered with a loading dose of cyclosporine, 10 mg/kg of body weight, before transplantation. Serum blood levels of cyclosporine, determined by radioimmunoassay, were maintained at 100 to 150 ng/ml. One gram of methylprednisolone was given during the transplantation procedure after separation from cardiopulmonary bypass. Prednisone, 1.0 mg/kg/day, was started after operation; the daily dose was reduced by 10 mg/week until a maintenance dose of 0.15 mg/kg was reached.

Results

Between February 1984 and April 1986, 31 patients underwent orthotopic cardiac transplantation at The Pennsylvania State University. Twenty-four patients are alive 3 weeks to 2 years after transplantation. Ten patients had a systolic arterial blood pressure of less than 90 mm Hg, a cardiac index of less than 1.8 L/min/m², a pulmonary capillary wedge pressure of greater than 25 mm Hg, and reduced renal blood flow as evidenced by a urine output of less than 20 ml/hr. These patients were in the intensive care unit and required invasive monitoring lines. Intravenous inotropic support alone sustained life in four patients for 3 to 18 days until a donor heart became available. In addition to inotropic support, six other patients required intra-aortic balloon support (Table I). Two of these patients required no further intervention before appropriate donor hearts became available. The intra-aortic balloon supported these two patients for 2 days and 14 days before the transplant procedure. The remaining four patients, in addition to inotropic and intra-aortic balloon support, required either a left ventricular assist device or a temporary total artificial heart to sustain life until a donor heart became available.

Two patients required the left ventricular assist device for 11 days and 21 days and are alive 3 weeks and 8 months, respectively, after transplantation. The pneumatic artificial heart supported one patient for 10 days before a donor heart became available. This patient subsequently died of septic shock 17 days after transplantation. Another patient required the total artificial heart after acute rejection of the cardiac transplant.

Left ventricular assist device as a bridge to transplantation

CASE I. A 24-year-old woman had New York Heart Association Class IV symptoms as a result of an idiopathic cardiomyopathy. Before her evaluation at our institution, the patient had been hospitalized on three occasions for increasing congestive heart failure. While undergoing evaluation for cardiac transplantation, the patient had a cardiopulmonary arrest. After successful resuscitation, her condition was hemodynamically unstable despite the administration of dobutamine and dopamine and insertion of an intra-aortic balloon
**Table I. Mechanical circulatory assistance as a bridge to cardiac transplantation**

<table>
<thead>
<tr>
<th>No.</th>
<th>Type of support</th>
<th>Duration of support (days)</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>I</td>
<td>3-18</td>
<td>Alive: 6, 8, 14 mo; dead: 7 mo</td>
</tr>
<tr>
<td>6</td>
<td>I, IABP</td>
<td>2-14</td>
<td>Alive: 10-11 mo</td>
</tr>
<tr>
<td>2</td>
<td>I, IABP, LVAD</td>
<td>11-21</td>
<td>Alive: 3 wk and 8 mo</td>
</tr>
<tr>
<td>2</td>
<td>I, IABP, TAH</td>
<td>10</td>
<td>Dead: 17 days postop.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+45</td>
<td>Waiting for transplant</td>
</tr>
</tbody>
</table>

Legend: I, Dobutamine and dopamine. IABP, Intra-aortic balloon pump. LVAD, Left ventricular assist device. TAH, Total artificial heart.

**Table II. Hemodynamics in a patient supported by an LVAD**

<table>
<thead>
<tr>
<th></th>
<th>Before admission</th>
<th>IABP + inotropic drugs</th>
<th>LVAD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3 mo</td>
<td>2 wk</td>
<td></td>
</tr>
<tr>
<td>BP (mm Hg)</td>
<td>110/75</td>
<td>100/70</td>
<td>89/63</td>
</tr>
<tr>
<td>RAP (mm Hg)</td>
<td>22</td>
<td>36</td>
<td>21</td>
</tr>
<tr>
<td>PAP (mm Hg)</td>
<td>45</td>
<td>53</td>
<td>44</td>
</tr>
<tr>
<td>PCWP (mm Hg)</td>
<td>26</td>
<td>28</td>
<td>32</td>
</tr>
<tr>
<td>CO (L/min)</td>
<td>5.20</td>
<td>4.60</td>
<td>3.85</td>
</tr>
<tr>
<td>CI (L/min/m²)</td>
<td>2.31</td>
<td>2.04</td>
<td>1.70</td>
</tr>
</tbody>
</table>

Legend: LVAD, Left ventricular assist device. BP, Blood pressure. RAP, Mean right atrial pressure. LAP, Mean left atrial pressure. PAP, Mean pulmonary artery pressure. PCWP, Pulmonary capillary wedge pressure. CO, Cardiac output. CI, Cardiac index. IABP, Intra-aortic balloon pump.

Pump (Table II). On July 18, 1985, the patient was taken to the operating room for implantation of a left ventricular assist device. Left ventricular apex cannulation was employed.

Postoperatively, the patient required prolonged respiratory support. Her respiratory status gradually improved, and she was extubated on postoperative day 13. She remained awake, alert, and lucid throughout her period of assistance. After extubation, the patient was able to tolerate an oral regular diet.

After 21 days of mechanical left ventricular assistance, a donor heart became available and the patient underwent an orthotopic cardiac transplantation. Her course after cardiac transplantation was uneventful, and she was discharged 30 days later. At no time during her hospitalization did the patient demonstrate any evidence of renal or hepatic dysfunction. She showed no signs of sepsis.

In April 1986, the patient continued to do well at home.

**Case 2. A 20-year-old man was healthy until January 1986, when an acute viral myocarditis developed. Congestive failure progressed and he was admitted for evaluation for cardiac transplantation. Hemodynamic deterioration led to the administration of dobutamine and dopamine and intra-aortic balloon pump insertion.** On March 22, 1986, a left ventricular assist device was inserted. Left ventricular apex cannulation was employed.

Postoperatively, the patient remained awake, alert, and lucid. He was extubated on postoperative day 1 and was able to resume a regular diet shortly thereafter. The patient had normal renal function. Congestive hepatic dysfunction, as evidenced by elevated liver enzymes and hyperbilirubinemia, rapidly resolved.

Eleven days after left ventricular assist device implantation, the patient underwent orthotopic cardiac transplantation. His post-transplant course was initially complicated by hypotension caused by a low systemic vascular resistance refractory to pressor administration and mild left ventricular dysfunction, which necessitated inotropic support and intra-aortic balloon pump insertion.

The patient's post-transplant course has also been complicated by oliguric renal failure necessitating intermittent hemodialysis and pancreatitis. The azotemia and hyperamylasemia are resolving. A *Pseudomonas aeruginosa* empyema is responding to chest tube drainage and appropriate antibiotic therapy.

**Total artificial heart as a bridge to transplantation**

**Case 3. A 44-year-old man with end-stage ischemic cardiomyopathy was transferred to our institution on Oct. 16, 1985, for evaluation for cardiac transplantation. Hemodynamic deterioration led to the administration of dobutamine and dopamine and intra-aortic balloon pump insertion.** On Oct. 18, 1985, unrelenting runs of ventricular tachycardia developed, unresponsive to drug therapy, which further accentuated his hemodynamic instability (Table III). The patient was taken to the operating room for implantation of a pneumatic artificial heart.

The patient demonstrated marked hemodynamic improvement after artificial heart implantation (systemic blood pressure 140/60 mm Hg, left atrial pressure 5 to 10 mm Hg, cardiac output index 3.0 L/min/m²). Postoperatively, he had normal renal function. Three days after artificial heart implantation, the patient became increasingly lethargic and eventually unarousable. Neurologic evaluation showed no focal signs. A metabolic workup was unrevealing. Computed tomography of the patient's head showed no evidence of acute hemorrhage...
or cerebral infarction. An electroencephalogram showed no seizure activity. The patient gradually awoke and postoperative day 6 was again lucid and conversant. On postoperative day 5, mild pancreatitis developed which appeared to respond to the discontinuation of enteral feedings. During the period of mechanical assistance, the patient was maintained on low molecular weight (10%) dextran (20 ml/hr) and aspirin (325 mg/day).

Ten days after artificial heart implantation, the patient underwent orthotopic cardiac transplantation, which was complicated by excessive bleeding. After transplantation, oliguric renal failure developed, necessitating daily hemodialysis, and a worsening of the pancreatitis, as evidenced by marked hyperamylasemia (2,830 U/L, normal 5 to 81 U/L), abdominal pain, and pancreatic enlargement on abdominal ultrasound. Trichosporon beigelii sepsis, unresponsive to amphotericin B administration, was the direct cause of this patient’s death 17 days after cardiac transplantation.

Autopsy revealed a widespread systemic fungal infection involving the pericardium, kidneys, spleen, mesentery, and colon. Acute hemorrhagic pancreatitis was also found.

CASE 4. A 48-year-old man underwent an aortic valve replacement in 1973. In July 1985, congestive heart failure developed. His symptoms progressed and on March 10, 1986, he underwent orthotopic cardiac transplantation. The immediate postoperative course was uneventful; however, on March 15, 1986, the patient had a cardiopulmonary arrest. After resuscitation, he required inotropic support. He was treated empirically for rejection. Sudden hemodynamic deterioration on the morning of March 17, 1986, led to intra-aortic balloon pump insertion. Despite balloon counterpulsation and the administration of dopamine (15 μg/kg/min) and epinephrine (4 μg/min), the patient’s cardiac output index fell to 1.54 L/min/m². He was returned to the operating room later the same day for artificial heart implantation.

Postoperatively, the patient remains awake, alert, and conversant. His course has been complicated by oliguric renal failure that initially necessitated daily dialysis. At present, his urine output is increasing and the frequency with which dialysis is needed has been reduced. Early, mild hepatic dysfunction, as evidenced by elevated liver enzymes and hyperbilirubinemia, is resolving. Mild pancreatitis, as evidenced by midepigastric abdominal tenderness, hyperamylasemia, and diffuse pancreatic enlargement on abdominal ultrasound, is also resolving. Forty-five days after implantation of the artificial heart, the patient remains neurologically intact and demonstrates no signs of sepsis.

**Table III. Hemodynamics in a patient with a TAH**

<table>
<thead>
<tr>
<th>HR (beats/min)</th>
<th>Admission</th>
<th>Inotropic drugs</th>
<th>IABP + inotropic drugs</th>
<th>TAH</th>
</tr>
</thead>
<tbody>
<tr>
<td>108</td>
<td>110</td>
<td>100</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>BP (mm Hg)</td>
<td>108/60</td>
<td>89/53</td>
<td>97/28</td>
<td>140/60</td>
</tr>
<tr>
<td>RAP (mm Hg)</td>
<td>20</td>
<td>18</td>
<td>22</td>
<td>6-13</td>
</tr>
<tr>
<td>PAP (mm Hg)</td>
<td>50</td>
<td>44</td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>PCWP (mm Hg)</td>
<td>42</td>
<td>30</td>
<td>28</td>
<td>5-10 (LAP)</td>
</tr>
<tr>
<td>CO (L/min)</td>
<td>3.56</td>
<td>3.48</td>
<td>2.63</td>
<td>5.60</td>
</tr>
<tr>
<td>CI (L/min/m²)</td>
<td>1.89</td>
<td>1.85</td>
<td>1.38</td>
<td>2.98</td>
</tr>
</tbody>
</table>

Legend: TAH, Total artificial heart. HR, Heart rate. For other abbreviations see Table II.

Discussion

This report demonstrates the usefulness of pneumatic ventricular assist pumps and the pneumatic artificial heart to provide temporary circulatory support in patients who, while awaiting cardiac transplantation, experience hemodynamic decompensation. Across the country, these devices have found a place as a bridge to transplantation.11 We have documented 17 cases in which ventricular assistance has been used as a bridge to transplantation (Table IV). Six patients have been supported by both left and right ventricular assist devices before receiving an allograft. Eleven patients have been discharged from the hospital after receiving a transplant. Also, we have documented 13 cases in which the total artificial heart has been used as a bridge to transplantation (Table V). In five cases the results have been good. It should be obvious that no one institution can accumulate the numbers of patients necessary to demonstrate ultimate survival rates of bridging procedures. In addition, it will take several years to accumulate 1 and 2 year survival rates after bridging procedures.

Hardesty and his colleagues13 have reported an actuarial 30 month survival rate of 75% for a group of 33 terminally ill patients requiring either intravenous inotropic support or diastolic augmentation before cardiac transplantation. They have shown that patients who have been sustained by intravenous inotropic and intra-aortic balloon support, as a bridge to cardiac transplantation, have long-term survival equal to that of patients who are in New York Heart Association Functional Class IV, but ambulant, and who are awaiting cardiac transplantation. Several years of continued clinical experimentation with the left ventricular assist pump and the total artificial heart as devices to bridge the time until transplantation are necessary to see whether or not their superb survival statistics can be duplicated in more severely ill patients.

The left ventricular assist device forms a third line of
support for patients whose left ventricular failure is not responsive to drugs or to the intra-aortic balloon. Current clinical experimental survival data (Table IV) favor the use of a single left ventricular assist device over the use of the total artificial heart if such a device will provide hemodynamic stability as a bridge to transplantation. Because the right and left ventricles work in series, poor right ventricular function will prevent a left ventricular assist device from achieving an adequate flow rate. The highest cardiac output that can be achieved will only equal the amount of blood pumped by the failing right ventricle. Thus one may pay a price to theorize that a patient requires a left ventricular assist device alone to achieve hemodynamic stability. In our patient, the function of the right ventricle responded well to the addition of continuous intravenous dopamine therapy. Had inotropic support failed, a right ventricular assist pump would have been used. Two patients supported by both left and right ventricular assist pumps before receiving the allograft have survived (Table IV).

If a single ventricular assist device will provide hemodynamic stability, it should be chosen rather than a total artificial heart. If a total artificial heart will fit into the patient’s chest, it is a better choice than biventricular assistance. We take this position because the waiting time for an appropriate donor organ to become available is unknown. Biventricular assistance necessitates four
large-diameter tubes to exit the skin and thereby increases the risks of infection. The longest period of biventricular assist support before transplantation has been only 6 days (Table IV, Case 4). If an absolute contraindication to orthotopic cardiac transplantation develops, the patient is committed to biventricular assistance for the remainder of his life.

Our first experience with the temporary use of a pneumatic artificial heart demonstrates one of the complex dilemmas associated with using these devices as a bridge to transplantation. There still remains the major risk of infection from the percutaneous drive lines and two surgical procedures on cardiopulmonary bypass. Infection is an absolute contraindication to cardiac transplantation. The ethical question of whether to proceed to the allograft procedure must be answered. The dilemma is made more complex, particularly in one of our patients, because we were unaware that he had an infection at the time of transplantation.

Disseminated Trichosporon beigelii (cutaneum) infection has been reported in 15 patients, all of whom had an underlying myeloproliferative disorder or malignant disease. To our knowledge, our patient is the first reported one with disseminated visceral Trichosporon beigelii infection who had no cutaneous manifestations. Blood, urine, and sputum cultures were sterile before placement of the allograft and for several days afterward. We were unaware of the yeast infection until several days after the transplantation was performed. Although one renal transplant recipient with localized pulmonary disease from Trichosporon beigelii has been reported, we know of no renal or cardiac transplant recipients with disseminated Trichosporon beigelii infection. Mortality associated with disseminated Trichosporon beigelii infection is over 80%, regardless of treatment.

At present, the most appropriate form of anticoagulation after temporary implantation of artificial devices is not known. Warfarin sodium (Coumadin) is the logical choice for long-term use of these devices, and all long-term animal experiments have used warfarin anticoagulation. However, the use of warfarin while awaiting a donor organ is impractical. We presently use low molecular weight dextran to inhibit platelet function and
Cardiac support followed by transplantation

thus far have not experienced thromboembolic phenomenon. In addition, no thrombus has been identified in our devices while this product has been in use.

In summary, a period of clinical experimental investigation is needed to demonstrate whether or not critically ill patients will achieve a long-term survival and rehabilitation that is equivalent to current survival rates and rehabilitation that follow orthotopic cardiac transplantation alone. If such results are achieved, the ethical questions must be answered as to whether bridging procedures are justifiable in our current status in which potential recipients far outnumber donor heart supply.

REFERENCES


Discussion

DR. DENTON A. COOLEY
Houston, Texas

I would like to discuss this important paper by Dr. Pennock and the group at the Hershey Medical Center because of my interest in staged cardiac transplantation, which dates back more than 17 years. From those early beginnings, I have believed cardiac transplantation to be a permanent solution to the problem of replacement of the terminally diseased heart.

Since 1982, when the Texas Heart Institute received permission from the Sandoz Corporation to use the new immunsuppressive drug, cyclosporine, 110 cardiac transplantations have been performed under the direction of Dr. Bud Frazier. He has accepted for transplantation patients considered by others to be unsuitable because of advanced age, presence of infection, and desperate general condition, and he has obtained remarkably good results.

Among the 110 patients in our series, 12 were supported before transplantation by intra-aortic balloon pumps for varying periods from 11 hours to 13 days. All survived transplantation.

Two patients have been supported by our service with intracorporeal left ventricular assist devices. The first assist device used for staged cardiac transplantation was implanted in 1978, and the most recent device, designed by Thermodynamics Inc., Woburn, Massachusetts, was implanted earlier this year. This latter patient was supported by the intra-aortic balloon pump for 8 days, followed by the assist device for 42 days. Six weeks after cardiac transplantation, the patient died of infection, seriously aggravated by alcoholic portal cirrhosis, which complicated his entire clinical course.

Three patients have undergone staged cardiac transplantation with total artificial hearts designed respectively by Drs. Domingo Liotta (1969), Tetsuzo Akutsu (1982), and Robert Jarvik (1986). Forty-eight hours after transplantation, the first patient to have an artificial heart implanted in the world was awake. What this single case proved was that the human central nervous system and human life could be sustained by a total artificial heart.

The most recent patient is a 42-year-old man with idiopathc cardiomyopathy. He was supported for 12 days with an intra-aortic balloon pump before implantation of a Jarvik-7 total artificial heart, which was used for 31 days before cardiac transplantation. After transplantation, a complicated chronol-
ology of events occurred. This man has received 151 units of blood from our blood bank, which has resulted in numerous problems from coagulopathy and infection. The patient is now recuperating in the hospital 8 weeks after transplantation.

Our experiences and those of others collected from the rapidly increasing surgical literature on staged cardiac transplantation provide strong confirmation of the concept and encourage further clinical trials.

DR. FELIX UNGER
Salzburg, Austria

The main indication for assisted circulation by means of left ventricular assist devices or biventricular assist devices is in patients with postcardiotomy cardiac failure, patients who are desperately ill. The total artificial heart has been designed to replace a heart failing because of cardiomyopathy.

The advantage of left ventricular assist devices or biventricular assist devices is that the heart is left in place and must not be removed. With these devices it is possible to perform functional heart replacement. The disadvantage is that the driving of the devices is more sensitive and the cardiac output of the pumps is diminished because of the cannulas. The artificial hearts are much easier to drive.

In March 1986 we were the first European group to implant an artificial heart in a patient with postcardiotomy cardiac failure. The patient had undergone a completely uneventful repeat aortic valve replacement and had been taken to the intensive care unit. Two hours later untreatable ventricular fibrillation developed. We returned the patient to the operating room and, after determining that we could not wean the patient from cardiopulmonary bypass, a second time, we had then to make this final decision.

We used the ellipsoid heart, which is made of polyurethane. The heart valves are Bjork-Shiley valves. The artificial heart was implanted for 24 hours. The patient recovered very well, and the transplantation was then performed by the Viennese group headed by Professor Wolner.

In Fig. A at the bottom is shown the arterial pressure of the artificial heart in a normal shape. The patient had constantly increasing spontaneous urine output. The circulation was stable enough so that the patient could recover.

What we learned from this procedure was that the artificial heart is a tool in patients with postcardiotomy cardiac failure, in patients who are desperately ill. Those patients must also have an indication for a subsequent transplantation.

My question to the Hershey group is this: Do you have exact guidelines in the patient group with postcardiotomy cardiac failure for use of left ventricular assist devices, biventricular assist devices, and artificial hearts?

DR. KIT V. AROM
Minneapolis, Minn.

I rise to discuss the Minneapolis Heart Institute experience.

On two occasions, in December 1985 and January 1986, we were involved in the approach that Dr. Pennock just described. The first patient was a 24-year-old man who in his early years had multiple congenital heart defects repaired by Dr. Aldo Castaneda. At that time mild aortic insufficiency had been noted. He had done well until shortly before admission, when annuloaortic ectasia developed. He received a composite graft on January 14 and had difficulty being weaned from cardiopulmonary bypass, most likely because of poor myocardial preservation. An intra-aortic balloon was inserted, and subsequently he received a Bio-Pump device (Bio Medicus, Minneapolis, Minn.) for left ventricular assist. During the first 24 hours, the left ventricular function appeared to be deteriorating despite a well-functioning left ventricular assist device. Fortunately, a heart donor became available and cardiac transplantation was performed. He did well and was discharged.

The second patient was a 40-year-old woman who was admitted to our institution with viral myocarditis and acute pulmonary and renal failure. On December 15 she received an intra-aortic balloon assist device and subsequently a total artificial heart, the Mini-Jarvik-7 heart. She did very well during the postoperative period. Her kidney function was improved, and on day 45 she had a cardiac transplantation. Unfortunately, she remains in the hospital with respiratory failure and renal insufficiency.

To my knowledge, the first case that I described represented the first successful use of the disposable centrifugal pump for
left ventricular assistance as a bridging procedure before cardiac transplantation. The second case represented the first use of an artificial heart in a woman and also the first clinical trial of Mini-Jarvik-7 heart, which has less stroke volume than the regular Jarvik-7 device that had been previously tried.

**DR. JACK COPELAND**  
Tucson, Ariz.

In Tucson we used the “Phoenix heart” in a 33-year-old man in March 1985. It was in place for 11 hours, he received a transplant, and he died. This device is currently still under development.

The next case at the University of Arizona involved a 25-year-old man who received a transplant in September 1985. A Jarvik-7 total artificial heart was implanted for 9 days before transplantation. To the best of my knowledge, this is the first successful use of a total artificial heart bridge to transplantation followed by long-term survival.

Our patient was in cardiogenic shock and receiving high-dose isotropic agents when the device was implanted. Bleeding was not a problem (690 ml in 24 hours). The device fit easily within his pericardium. He was fully awake and neurologically intact, and he lost 18 L of fluid during the first 4 days after implantation. Hemolysis was not a problem.

He did have a tiny stroke, characterized by a reversible (3 week) period of expressive aphasia. Computed tomographic scans of his head showed no abnormalities. He is now back to full-time work 8 months after cardiac transplantation and is completely normal.

We believe that a minority of patients with end-stage heart disease will require mechanical support. We also believe that after mechanical heart implantation a period of time should follow which allows recipients to meet all protocol criteria for heart transplantation before one proceeds to cardiac transplantation.

Dr. Pennock, do you agree with this philosophy of waiting until a patient is stable before going on to cardiac transplantation, or, as some people have suggested, should transplantation be done as soon as possible?

**DR. CHRISTIAN CABROL**  
Paris, France

In any active program of cardiac transplantation, the situation will occur in which an otherwise perfect recipient candidate sustains an acute and irreversible decompensation and dies before cardiac transplantation can be undertaken. Dr. Pennock has shown us that in such cases the present methods of mechanical circulatory support can maintain an adequate circulation until an appropriate donor heart can be found and a successful transplantation accomplished. This was demonstrated for the first time in November 1984 by the Stanford group, which performed a successful transplantation in a patient after 8 days of mechanical support of the circulation with a Novacor pump.

Our experience encompasses 225 cases of cardiac transplantation. We have used such mechanical devices in the last 6 months on three patients. Only one of them, an 11-year-old boy, was successfully brought to cardiac transplantation after 12 hours’ support of the left ventricle with a paracorporeal Lotta Bioimplant ventricular assist device and support of the right ventricle with a standard roller pump.

However, to avoid filling the waiting list for transplantations with bad candidates who would not benefit from the subsequent transplant operation, such indications must be restricted, in our opinion, to patients who would otherwise fulfill the usual criteria for acceptable recipients. Also included, as Dr. Copeland said, would be patients who can be returned to this state after a sufficient period of improvement obtained with mechanical circulatory support, and more easily obtained in selected cases by the use of a total artificial heart such as the Jarvik-7, which we started to use.

Dr. Pennock, do you agree with this opinion and, in that case, what would be your procedure of choice?

**DR. WILLIAM A. GAY, JR**  
Salt Lake City, Utah

Of the first 10 patients receiving pneumatic-powered orthoptic artificial hearts, three were survivors. Eight of the second 10 have survived. This represents significant progress. Maybe it is a learning curve: maybe the devices are getting better. This is an important tool that we need to keep studying, and I would urge the group from Hershey, as well as others who feel so inclined, to keep investigating these very important devices.

I have one question for Dr. Pennock: Do these persons on ventricular assist devices or total artificial hearts go to the top of the transplant list or the bottom of the transplant list?

**DR. PENNOCK (Closing)**  

It is obvious that the donor supply is smaller than the number of recipients waiting for organs in a given year in this country. It is important to look at this work as an experimental protocol to see, in individual patients, what we are capable of achieving in modern medicine. Therefore, it is an experiment and should be controlled.

Dr. Unger asked about guidelines of using an artificial heart versus a left ventricular assist device in a postcardiotomy situation: The ideal patients for bridging procedures are patients who have been worked up for a heart transplant. All the social, economic, and psychological aspects of their cases have been discussed in full. Their opinions and desires for or against bridging procedures have been discussed. They have passed all the medical criteria for being transplant recipients. Therefore, if they enter a state of cardiogenic shock with their end-stage heart disease, everything has been determined before they are taken to the operating room.

We personally would not implant a total artificial heart, a pneumatic artificial heart, into a patient whom we could not wean from bypass, from an elective or emergent procedure, because the ramifications have not been discussed with that patient concerning what it is to be alive with an artificial heart.

The questions by Dr. Gay and Dr. Copeland are appropriate
questions. This experiment must demonstrate over a period of time that we are able to achieve survival rates in patients undergoing transplantation alone. If we cannot accomplish this, then we are wasting organs.

Therefore, it is our opinion that patients who receive these devices are not on any transplant list until they have recovered all organ function and are then medically acceptable for transplantation, just as they were before the devices were implanted. If a contraindication develops, such as infection or end-organ failure of any of the vital organs, we would not proceed to an allograft procedure.

They are listed as Status 9. However, we would not deny an organ to another Status 9 patient who did not have an assist device or total artificial heart within his chest. We believe our patients are stable and can wait longer.