Blood-Pool Radionuclide Angiography in Patients with a Novacor Left Ventricular Assist Device

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Blood-pool radionuclide angiography was used to investigate the left ventricular function in eight patients who received a Novacor assist device as a bridge-to-cardiac transplantation. Studies were performed during maximal and minimal tolerated assist device flows. The left ventricular ejection fraction, volumes, cardiac output, and the pump ejection fraction were computer-assessed. All patients had severe left ventricular dilation and hypokinesis before insertion of the assist device, with a mean ejection fraction of 18% ± 4% which improved to 44% ± 18% ($p < 0.01$) during maximal assist device flows, but fell to 25% ± 15% ($p < 0.01$) during minimal flows. The ventricular volumes became normal at maximal assist device flow but increased significantly ($p < 0.05$) during minimal flow. The pump was well visualized and had an ejection fraction of 82% ± 7%. These data indicate that this assist device effectively unloads the left ventricle. The deterioration in ejection fraction following decrease in assist device flow is in keeping with the dependency of these patients on the device to sustain adequate hemodynamics.

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During the past few years, various means of mechanically supporting patients with heart failure have been used as a bridge-to-cardiac transplantation. Devices utilized have ranged from the intraaortic balloon pump to the total artificial heart. These devices have some inherent problems, the most important of which is the thrombogenic potential of the blood-device interface, which may be the site of thrombosis and subsequent embolism. The Novacor (Oakland, CA) assist device (AD) has been designed in such a manner so as to minimize the possibility of thrombus formation, allowing prolonged circulatory support. Although excellent clinical results have been obtained with this system, there is a paucity of information with respect to the cardiac function in patients with a Novacor AD. Blood-pool radionuclide angiography (RNA) has been used in the assessment of the total artificial heart (*1–3*) as well as for studying the ventricular function in patients with assisted circulation by a centrifugal pump (Biomedicus, Minneapolis, MN) AD (*4*). The objective of our investigation was to study left ventricular (LV) function in patients with a Novacor AD using blood-pool RNA.

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MATERIALS AND METHODS

We studied eight patients, 7 males and 1 female, mean (± s.d.) age 53 ± 10 yr (range 39–66 yr), who suffered from chronic, severe heart failure, refractory to i.v. therapy with inotropic agents, vasodilators, and diuretics. All patients signed informed consent forms, which were approved by the Institutional Review Boards for Human Research, and received the AD as a bridge-to-cardiac transplantation.

The underlying cardiac pathology was ischemic cardiomyopathy in six and idiopathic cardiomyopathy in two patients. Three of the patients had previously undergone coronary artery bypass graft surgery. An intraaortic balloon had been placed in two patients before the AD implantation; however, the balloon alone proved insufficient to sustain adequate hemodynamics. Two patients had previously received a Biomedicus AD, which was subsequently replaced with a Novacor AD. Within 4 wk prior to the AD implant, all patients had a left ventricular ejection fraction (LVEF) assessment, which was done by RNA in four and by two-dimensional echocardiography in four patients.

Description of the Pump

This system utilizes a microprocessor-controlled solenoid energy converter coupled with a dual pusher-plate blood pump. The major subsystems include the energy converter (which transforms electrical to mechanical energy), blood pump, electronic control and power unit, and primary power module with status monitor. The blood pump consists of a smooth-surfaced polyurethane sac that is attached to two diametrically opposed pusher plates. The blood pump and energy converter are integrated into a single compact unit fitted with two bioprosthetic valves and inflow and outflow conduits. The pump is implanted anterior to the posterior rectus sheath in the upper quadrant of the abdomen (Fig. 1).

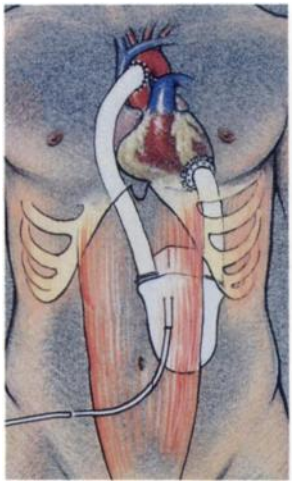

FIGURE 1
Artist's conception of the Novacor assist device in place.

The AD is inserted into the patient during cardiopulmonary bypass. The inflow conduit is tunneled through the anterior portion of the left hemidiaphragm to the left ventricular apex. The outflow conduit is brought through the right hemidiaphragm anteriorly in the midclavicular line and anastomosed to the ascending aorta. The pump has a maximal stroke volume of 70 ml. The external console monitors physiologic parameters of the pump (stroke volume, residual systolic volume, filling and emptying rates), as well as the patient's heart rate and guides performance optimization of the AD.

The pump may be triggered by the patient's ECG ("ECG trigger mode"), or more preferably, it is synchronized to the filling rate of the pump ("filling rate trigger mode"). It may also function at a prefixed rate ("fixed rate trigger mode"). Filling of the pump starts when the pressure begins to increase in the ventricle, during isometric contraction, and surpasses the pump pressure, opening the inflow valve. Very small gradients, on the order of a few mm of Hg are capable of opening the valve, a situation similar to that which exists with prosthetic aortic, mitral, or tricuspid valves. The pump ejection is completed before the onset of the next ventricular systole. Thus, this system allows the LV to function under a very low afterload.

Filling of the pump may be varied by changing the pump filling delay, which causes the pump to stay closed for longer periods of time. As a consequence of delayed opening of the pump, the ventricle must generate a higher intraventricular pressure prior to filling the pump. Thus, by increasing the filling delay, one effectively varies the afterload of the LV. This intervention may be used during testing of the LV function and during the weaning procedure.

Radionuclide Angiography

Blood-pool RNA was performed at bedside using a mobile, computerized single crystal gamma camera (Technicare 420-550) and a general-purpose collimator, utilizing a modified in vivo red blood cell labeling technique with technetium-99m, as reported from our laboratory (*5*), from 3 to 32 days (average 14 days) after implantation of the AD. In seven patients, the LV function was studied with the pump at maximal flow (no filling delay) and at the minimal tolerated flow (filling delay activated). The minimal tolerated flow was, by necessity, different from patient to patient. After each change in AD flow, 5-min intervals were allowed for hemodynamic stabilization prior to image acquisition.

LVEF, LV volumes, and cardiac output were calculated using a count-based method, previously validated in our laboratory (*5*). Left ventricular regional wall motion was visually assessed on cine mode display. The RVEF could not be calculated in several cases because of overlap in the left anterior oblique view between the blood-filled outflow conduit and the RV and, thus, is not reported.

We also obtained gated images of the pump implanted in the abdomen, in the anterior view, and for a preset time of 300 sec. The pump EF was calculated using a fixed region of interest.

Statistical Analysis

The data are reported as mean ± standard deviation. Group comparisons were done using paired Student's t-tests. A p value of < 0.05 was considered significant.

RESULTS

The changes in LVEF are illustrated in Figure 2. Before the AD implant, all patients had LV dilation and severe, diffuse hypokinesis. LVEF ranged from 12% to 25% (mean 18% ± 4%). After AD implantation and at maximal AD flow, the EF improved significantly ($p < 0.01$ versus pre-implantation) to 44% ± 18% (range 13% to 70%). In the four cases with pre-implant RNA studies available for review, the visually assessed LV end-diastolic volume (EDV) and end-systolic volume (ESV) decreased markedly after the AD implant. Post-AD implantation, EDV ranged from 72 to 193 ml (mean 137 ± 58 ml) and ESV ranged from 31 to 121 ml (mean 74 ± 34 ml). Both EDV and ESV mean values are within normal limits (*6*).

The apex of the heart was always akinetic because it was the site of connection between the inflow conduit of the pump and the LV. The posterolateral wall had the best motion, whereas the interventricular septum was generally hypokinetic or akinetic, as often seen after open-heart surgery.

LV Function During Minimal AD Flow

During minimal AD flow, LVEF decreased significantly ($p < 0.01$ versus maximal flow) to 25% ± 15%

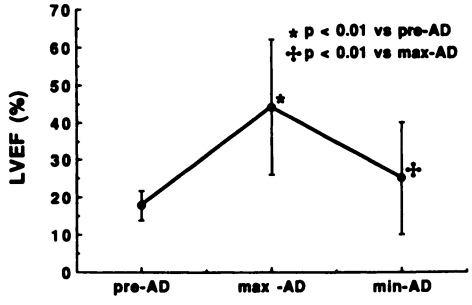

FIGURE 2
LVEF before and after implant of the Novacor assist device.

(range 13%–55%) (Fig. 2). The changes in LV volumes during minimal AD flow are summarized in Figure 3. Left ventricular EDV increased ($p < 0.05$) to 169 ± 79 ml (range 76–245 ml) and ESV increased ($p < 0.02$) to 127 ± 52 ml (range 66–178 ml). The RNA-determined cardiac output decreased from 6.7 ± 3.5 l/min to 4.8 ± 3.5 l/min ($p < 0.01$). During the pump's operation at minimal flow, the most dynamic segment of the LV was also the posterolateral wall, whereas the apex was akinetic and the interventricular septum akinetic. In one patient, the EF was unchanged during minimal AD flow; the EF in the same patient, before and after the AD implant, remained exactly the same (13%).

The RNA images of a patient who received the Novacor AD is illustrated in Figure 4, before and after the AD implant.

AD Pump Images

Images of the AD pump are illustrated in Figure 5. Nearly complete emptying was seen in all cases. The pump EF ranged from 71% to 89% (mean 82% ± 7%).

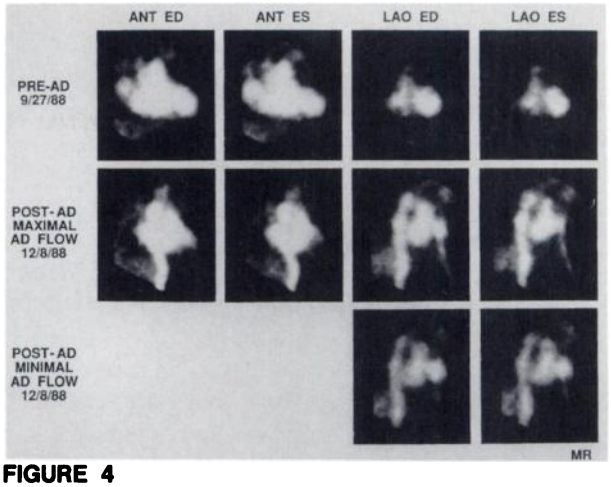

FIGURE 4
Blood-pool radionuclide angiograms of a patient before assist device implant (upper row), after the implant at maximal assist device flow (middle row), and at minimal flow (lower row). Marked decrease in left ventricular volumes and improvement in function can be appreciated. Left ventricular dilation and decrease in EF are seen during minimal assist device flow. The EF was 12% before the assist device implant, 56% at maximal assist device flow, and 13% at minimal flow.

DISCUSSION

In this study, we report the use of RNA to assess LV function in patients with an LV Novacor AD. We also show that it is feasible to study pump function by RNA. In fact, this may be the only noninvasive technique capable of simultaneously assessing the function of the LV and of the AD pump during assisted circulation. In addition, RNA allows excellent visualization of the connection of the pump with the heart and of the general structure of the pump, especially during cine mode display.

LVEF volumes, stroke volume, and cardiac output were calculated when the pump was fully operational and when it worked at minimal flow. Before the pump insertion, patients had LV dilation and severe, diffuse hypokinesis. With the pump working at maximal flow (low resistance), LVEF was much higher and LV volumes were smaller, as compared to the preoperative period, because the LV operated at a very low afterload. Hence, with the AD fully operational, the LV empties predominantly, if not exclusively, into the abdominal pump, at a low LV-developed pressure. Small intraventricular pressures are sufficient to open the pump's inflow valve, in contrast with the higher pressure required to open the aortic valve (dictated by the diastolic arterial pressure). However, when the resistance of the pump was increased by increasing the filling-delay, greater LV work was necessary in order to generate a higher intraventricular pressure, sufficient to open the AD inflow valve or the patient's aortic valve. At that time in the face of an abrupt increase in afterload, the LV dilated acutely and there was a marked fall in LVEF.

Thus, it is likely that the apparently improved LV function during maximal AD flow resulted simply from the very effective LV unloading by the AD. Conversely, deterioration in LV function during minimal AD flow is likely to be secondary to the increase in afterload.

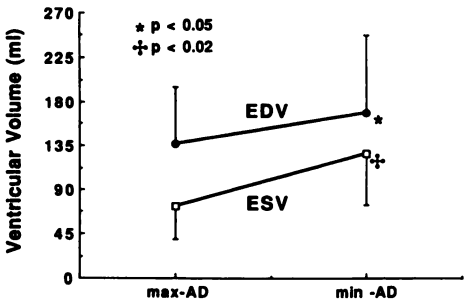

FIGURE 3
Left ventricular volumes during maximal and minimal assist device flows.

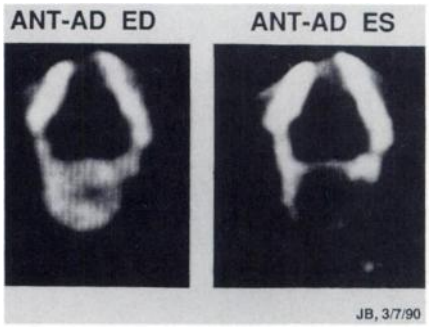

FIGURE 5
Blood-pool radionuclide images of the Novacor assist device located in the patient's abdomen. Notice the almost total emptying of the assist device sac at end-systole.

The true contractile state of the LV is probably unchanged during maximal or minimal AD flows. Poor LV performance during minimal flow certainly indicates dependency on the AD to maintain an adequate systemic circulation. Furthermore, in these cases, short-term Novacor AD sustenance did not allow recovery of native LV function to a point where the pump was no longer necessary.

Gated RNA also allowed us to study the AD pump. We noticed an almost complete emptying of the pump, although the pump's EFs, determined by RNA, were slightly lower than expected—the pump's residual volume is approximately 10% of the filling volume, with a mean predicted EF of 92%. This discrepancy may be due to difficulties in identifying the pump's valve planes, which may have falsely elevated the end-systolic counts.

The observations we have made with the Novacor AD differ from those we have previously reported with the Biomedicus AD, in which decreases in AD flow led to increases in EF (*4*). The EF increment proved to be a good predictor of patients who could be weaned from the AD. There is, however, a major mechanical difference in cannulation between the Biomedicus and the Novacor AD. In the patients receiving the Biomedicus device, the heart cannulation is from the left atrium, whereas in patients receiving a Novacor AD, it is from the LV. Therefore, in the Biomedicus device, a decrease in pump flow increases the preload but does not increase the ventricular afterload because the LV is always ejecting into the aorta. Patients who receive the Biomedicus pump typically have a greater potential for improving LV function, since the predominant clinical scenario for use of this AD is that of perioperative myocardial stunning which may be reversible (*7*). In contradistinction, patients who receive a Novacor AD usually have chronic, irreversible cardiac failure and undergo the pump implant as a last resort to sustain life or as a bridge-to-cardiac transplantation.

Despite the marked improvement in hemodynamics and amelioration of congestive heart failure that are brought about by the Novacor AD implant, these patients remain AD-dependent. As demonstrated, RNA provides important physiologic information concerning the function of the LV assisted by a Novacor AD. This information may be particularly critical when totally implantable devices, which are not connected to an external console and are presently being tested in animal experiments, are available for human use.

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