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CARDIOLOGY Rounds™

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Ventricular Assist Devices

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Introduction

The term ventricular assist device, or VAD, describes any of a variety of mechanical blood pumps employed singly to replace the function of either the right or left ventricle. Two blood pumps can be utilised for biventricular support. For left ventricular assistance, blood is withdrawn from either the left atrium or the apex of the left ventricle and is returned to the aorta.[1] Initially these devices were developed for very short term support of patients after cardiac surgery with cardiogenic shock unresponsive to pharmacologic manipulation; patients who were otherwise expected to improve if given a "bridge". The use of VAD's have expanded to include patients awaiting cardiac transplantation who are refractory to medical therapy and would otherwise die before a donor organ became available.

Historical Perspective

Attempts to replace the pumping action of the heart with a mechanical device date back to 1929, when Gibbs described a contrivance made to replace the function of the left and right ventricles in animals.[2] In 1966, Debakey[3] described use of a valved, pulsatile left ventricular assist device that withdrew blood from the left atrium to support a patient after surgery to replace severely regurgitant mitral and aortic valves. This artificial pumping chamber received blood via an inflow cannula attached to the left atrium which was then returned via an outflow cannula to the systemic circulation connected to the right axillary artery. The patient was in severe heart failure preoperatively and postoperatively remained supported by the assist device for ten days. Two attempts to wean off device support on post-operative day four and seven were complicated by worsening heart failure and hypotension. Gradual recovery of the ventricle allowed the mechanical pump to be removed on the tenth day; the patient survived to discharge, and eventually returned to work. This case represents the first successful use of a pulsatile mechanical assist device. The first human total artificial heart was implanted as a bridge to transplantation by Cooley[4] in 1969. These early successes was the impetus for the creation of a program to develop such devices in the United States, formally funded by the National Heart Lung and Blood Institute (NHLBI).[5] Since the 1970's, a plethora of devices have become available.

Types of Devices

Devices may be classified as pulsatile or nonpulsatile, intracorporeal or extracorporeal (Table 1). There are a plethora of devices now available and only a brief overview is included.

A. Non pulsatile extracorporeal devices

These devices, when used for left ventricular assist, remove blood via a cannula from the left atrium or ventricle and circulate it through and external pump, returning the blood to the arterial circulation, usually the ascending aorta. A simple roller pump[1] has been utilised; tubing of the extracorporeal circuit is placed in a roller head and forward flow is imparted to blood by rotating occlusive rollers. A centrifugal pump[6] (Figure 1), usually a rotating cone that draws in blood and propels it forward using centrifugal force, is preferred as there is less trauma to blood elements.

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Table 1: Comparison of more commonly used ventricular assist pumps

VAD type	Name	Manufacturer	Advantage	Disadvantage
Roller	Roller	Many	Readily available Simple to use Inexpensive	Flow limitation Blood trauma Tubing spallation Nonpulsatile Systemic anticoagulation Short term use Constant supervision needed
Centrifugal	Bio-Pump Centrimed Isoflow	Medtronic Inc. Sarns Inc./3M Arles Medical/St. Jude	Readily available Simple to use Relatively inexpensive Less blood trauma	Nonpulsatile Systemic anticoagulation Constant supervision needed
Pulsatile	BVS 5000 Bi-ventricular Support System HeartMate 100 LVAS Thoratec VAD System Novacor N-100 Penn State	Abiomed Inc. ThermoCardiosystems Inc. Thoratec Laboratories Corp. Novacor Medical Division, Baxter Healthcare Corp Arrow International, Inc.	No blood trauma +/– anticoagulation Pulsatile flow Minimal supervision needed	Expensive

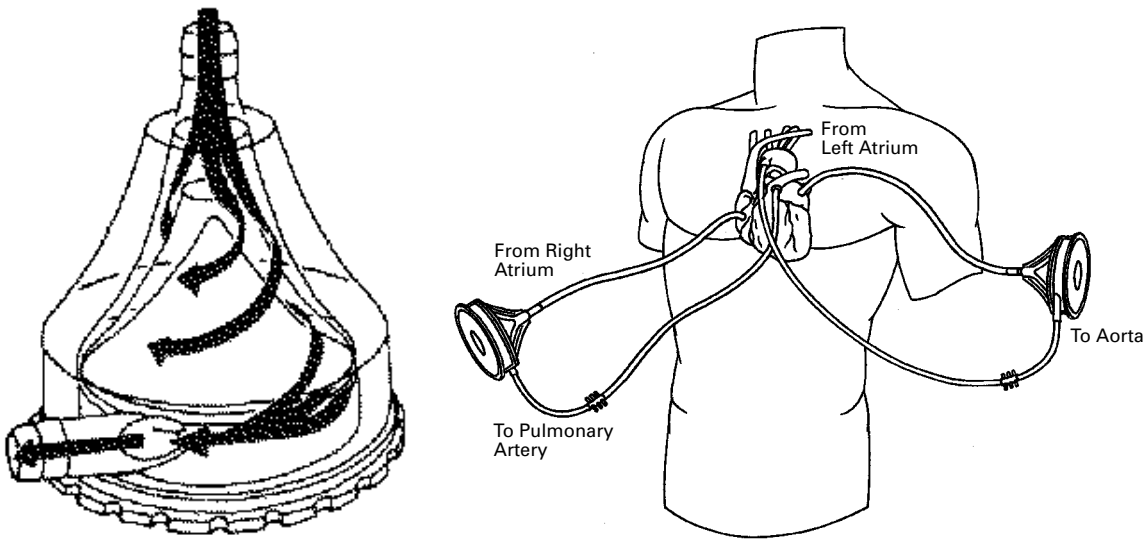
Adapted from Richenbacher WE, 1997[1]

The advantages of such devices include relative ease of insertion, use for both right and left heart support, and availability. These devices have been used successfully, and continue to be used, for post cardiotomy cardiogenic shock and as a bridge to transplantation.[7-10] Their use is limited by a) bleeding requiring operative reexploration, then paradoxically b) thromboembolism within the cannula requiring systemic anticoagulation, c) infection and the d) use of nonpulsatile flow. Generally useful for short-term support, it has been utilised for periods of up to 31 days.[10] More commonly used centrifugal pumps include the BioMedicus pump and the Centrimed Delphin pump.

B. Non pulsatile intracorporeal devices

These devices utilise axial flow pumps, which are based on the principle of Archimedes that a rotating screw in a tube can transport liquid. The Hemopump™ (Figure 2) is a catheter mounted intraaortic transvalvular axial flow LVAD. The pump is housed in a 21 French sheath with an inlet cannula designed to cross the aortic valve into the left ventricular cavity. The intraventricular axial flow impeller rotates from 15,000 to 27,000 rpm.[6,11] Blood is withdrawn from the left ventricle and returned to the descending aorta. The hemopump can be place percutaneously through the common femoral artery and positioned with fluoroscopic guidance; the ease of insertion, without the need, for sternotomy is a primary advantage. The pump is capable of flows of 4.5 L/min.[12] The experience with device remains quite limited; systemic anticoagulation is required, there is a degree of blood trauma, it is difficult to insert in patients with small body habitus and contraindicated in patients with peripheral vascular disease.[6] Its use has been reported

Figure 1

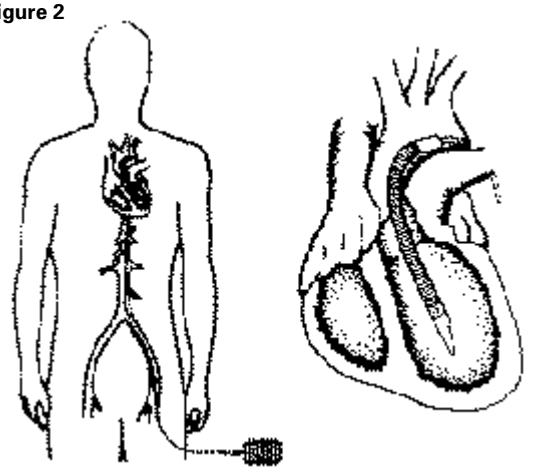


The centrifugal pump used for biventricular support. The centrifugal pump imparts forward flow to blood using a vortex with a rapidly spinning series of cones. From Richenbacher WE, 1997.[1]

in cardiogenic shock from myocardial infarction as well as post cardiotomy.[13-15] Only mild hemolysis was detected, although severe thrombocytopenia requiring transfusion was reported.[7] In one patient, a mural thrombus was aspirated by the hemopump causing acute device failure.[7] A 14 Fr device also exists for use in the cardiac catheterization lab. Although the device has not received premarket FDA approval in the United States,[6] it is in clinical use in Europe where a trial is planned to compare the hemopump to the intraaortic balloon pump.[12]

A fully implantable axial flow device, the Jarvik 2000 Axial Flow Assist Device, has been developed with the intention of long term use.[12] Slightly larger than a double A battery, a thoracotomy is performed to place the impeller directly in the LV with an outflow graft to the aorta. It achieves a pump speed of 8000-12000 rpm (2-10L/min) and the motor operates on 5 W batteries. Although no human subjects have as yet received such a device, animals have been supported for up to and over 150 days.[16]

Figure 2

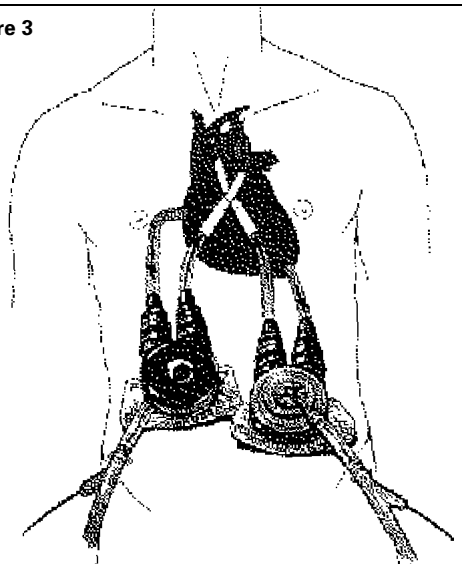


Hemopump placed through femoral artery and guided into left ventricle. From Votapka TV et al, 1994.[6]

C. Extracorporeal pulsatile devices

Pneumatically driven extracorporeal pulsatile assist devices may be used for left, right, or biventricular support.[11] The devices have an external power and control console with limited patient mobility. The Pierce-Donachy Assist Device is one such VAD; it has been in clinical use since 1976. The device contains Bjork Shiley valves to provide unidirectional blood flow. The diaphragm is actuated pneumatically by an external console, and is capable of maximum device output of 7 L/min. Left ventricular assist uptake cannulas may be placed in the left atrium or left ventricular apex, while the outflow cannula is placed in the ascending aorta. The right ventricle can be supported with a separate device with cannulas in the right atrium and main pulmonary artery. All cannulas exit the chest below the costal margin, with the device resting on the abdomen.[11] Patients require systemic anticoagulation, and the risk of infection with multiple exteriorized conduits is significant. Clinical experience with this device has been limited to post cardiotomy cardiogenic shock and bridging to transplantation.[17-19] Other such devices include the Abiomed BVS-5000 and the CardioWest, Inc. Ventricular Assist Device.

Figure 3

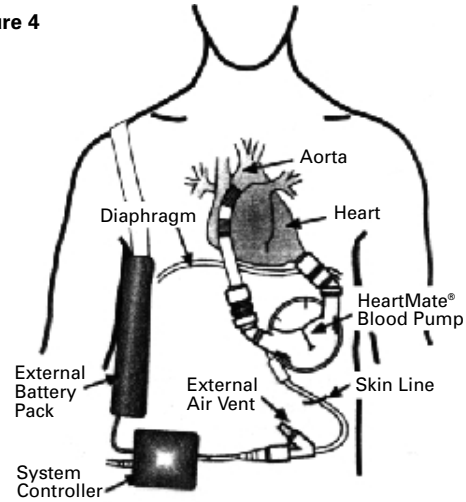


Pierce-Donachy paracorporeal assist device used for biventricular support. From Votapka TV et al, 1994.[6]

D. Intracorporeal pulsatile devices

The mechanical pumping chamber is completely implanted with an external power and control console. The two devices more commonly available are the HeartMate™ and the Novacor LVAS™.[6,11] Blood enters the pump from the left ventricle and is ejected into the aorta via an electrical or pneumatic pump. Inflow and outflow ports are fitted with tissue valves. The pump is buried in an abdominal wall pocket, and conduits are tunneled across the diaphragm to connect to the left ventricular apex and ascending aorta. An external electrical power cable and venting system are tunneled subcutaneously before exiting the skin. They can only be used for left ventricular support

Figure 4



HeartMate. The diagram shows how an LVAD "heart pump" is hooked up to the heart and to its external controller and power supply. From Votapka TV et al, 1994.[6]

and the complications of infection and thromboembolism remain. The clinical experience with these devices has been as a bridge to transplantation.[20-23]

Complications

Infection

Infection remains a formidable obstacle to device use. Serious implantable VAD infections with documented bacteremia occurs in 50% of patients with devices in situ for over 30 days.[24,25] Transcutaneous energy transfer systems have been developed that obviate the need for externalized components that theoretically reduce the rate of infection; however, little data is presently available with these systems.

Thromboembolism

Despite systemic anticoagulation, thromboembolism continues to be another major complication of most VAD systems, especially those devices employing long extracorporeal conduits. A conspicuous exception to this observation is the HeartMate implantable pulsatile implantable device: the reported thromboembolic rates range from 0-4%[22,23,26] despite the adjuvant use of antiplatelet agents only. This astonishingly low incidence of thromboembolism has been attributed to the specially textured blood-device interface. During the development of the HeartMate, multiple studies were undertaken with smooth Silastic bladders in the 1960's that had to be abandoned because of the rapid accumulation of thrombus in the pump the thromboembolic damage to vital organs.[5] Eventually a textured surface of titanium spheres, diffusion bonded to the titanium blood pump was developed that, in long term use, encourages the formation of a thin cellular lining that does not appear to be thrombogenic.[27] Although not fully understood, study of this lining has demonstrated cellular elements embedded in a collagen fibrin matrix that is adherent to the textured surface and is formed within a few days. The cellular elements consist of spindle cells resembling fibroblasts, myofibroblasts, hematopoietic cells that are mostly of monocytic or myeloid lineage, as well as a few pluripotent hematopoietic cells.[28-30]

Right ventricular failure

Refractory right ventricular failure is a complication for 20-30% of patients who receive LVAD support.[31] Increased venous return produced by an LVAD can affect right ventricular function by increasing preload. An increased right ventricular free-wall-to-septum dimension corresponding to a decreased left ventricular free-wall-to-septum dimension during left ventricular unloading has been demonstrated.[32] Because of interventricular dependence, when left ventricular pressure or volume is reduced, right ventricular developed pressure is also reduced.[33,34] In the setting of a normal pulmonary vascular bed, the decrease in left sided filling pressures will decrease pulmonary artery pressures and right ventricular afterload. Thus, with LVAD support, the increase venous return and decreased contractility of the right ventricle is offset by the reduction in right ventricular afterload and right ventricular cardiac output is preserved.[35] If however, there is primary dysfunction of the right ventricle or a fixed increase of pulmonary artery pressures, the right ventricle can fail with the induction of LVAD support.[35,36] Biventricular support devices are available and are recommended if primary right ventricular dysfunction or a fixed increase in pulmonary vascular resistance is suspected.[36]

Permanent use of implantable devices

Thus far, the use of VAD's has been in the setting of desperately ill patients who remain in cardiogenic shock despite full inotropic and intraaortic balloon counterpulsation support after cardiac surgery or while awaiting transplant. Such patients almost assuredly would not survive without the short term support of an assist device and many remain critically ill despite the implantation of a VAD. It has been of more importance to the cardiovascular surgeon and of passing interest to general cardiologists. However, the indications are expanding as the technology and clinical use of these devices advances; it seems inevitable that cardiologists will begin to see patients on long term mechanical support in their practices and will have to consider the option of device therapy for their patients with end stage heart failure. Inadvertently, VAD's originally implanted for bridging to transplantation have become long term therapeutic devices as the waiting lists for transplantation grows longer.[37] Frazier described the use of a HeartMate LVAD in a 33 year old man initially bridged to transplant during cardiogenic shock who survived for 16 months before succumbing to a stroke. During this interval, the patient was in NYHA class I condition and was discharged home able to care for himself and participate in limited recreational activities such as shooting baskets.[38] An FDA approved protocol for graduated discharge and outpatient management of patients bridged to transplant with an LVAD now exists.[39,40] The prospect of outpatient permanent LVAD support *in lieu* of transplantation for the treatment of endstage heart failure refractory to medical management appears to be looming in the horizon for certain patient populations. Smaller battery packs and control consoles make the devices minimally inconvenient. The significant risk of infection may be substantially reduced by the development of completely implantable devices and transcutaneously transferred energy and may be comparable to the significant risk of infection complicating the aggressive immunosuppressive regimens required for transplantation. Clearly, the results of sound randomized clinical trials comparing the VAD to medical therapy and transplantation are required to determine the place the device should occupy in the treatment of advanced congestive heart failure.

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Abstracts of Interest

The Benefits of Earlier Selection for Ventricular Assist Device (LVAD) Placement in Low Output States

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Previous studies have shown poor survival rates when refractory shock is used as a criterion for LVAD placement. To evaluate the efficacy of earlier LVAD placement a retrospective review was conducted of in patients with severe, inotrope refractory heart failure treated with (n=24) or without (n=18) a LVAD. All patients were NYHA Class IV. The treatment and control groups were similar in gender (88% vs. 70% males, p=0.133), age (48±12y vs 49±15y, p=.802) and etiology of heart failure (58% vs 67% ischemic, p=NS). Patient acuity, assessed by APACHE II scores (which evaluate and aggregate the degree of physiological derangement of 12 different parameters), was similar in both groups at presentation (treated vs control, 14±5 vs 13±7, p=NS). The two groups also had similar Charlson comorbidity scores (1.8±1.1 vs 2.2±.8, p=.223), baseline bilirubins (1.8±1.0 mg/dl vs 1.4±1.2 mg/dl, p=.293), and creatinines (1.4±0.8 mg/dl vs 1.4±0.7 mg/dl p=.962). Intraaortic balloon pumps were used in 6(24%) treated and 8(40%, p=.26) control patients. **Results:** Twenty-three treated and 3 control patients have been transplanted. Five controls were revascularized and 8 controls are listed for transplant. Infections occurred in 10 treated and 5 control pts. (p=.187) and transfusions were required in 10 treated pts. (p=.003). Survival analysis revealed better overall survivorship in treated patients (Log Rank test, p=.02) with an in-hospital survival of 92% versus 72% for control patients. **Conclusion:** Although randomized control trials are still necessary, this study supports a strategy of early LVAD placement as a bridge to transplant in patients with inotrope refractory heart failure prior to development of severe multiple organ dysfunction.

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Nitric Oxide (NO) Inhalation in the Treatment of Right Ventricular Failure Following Left Ventricular Assist Device (LVAD) Implantation

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Following LVAD implantation in end-stage heart failure, the management of right ventricular failure (RVF) in the immediate postoperative period presents one of the most challenging therapeutic problems unresolved by means of conventional drug therapy (catecholamines, nitrates, prostacyclin). The effects of supplemental NO therapy were investigated postoperatively and prospectively: Pulmonary hemodynamic parameters and systemic pressures were measured invasively, right ventricular function (RVEF, RVEDV) was evaluated by repeated transesophageal echocardiography. To determine the most effective dose of NO (15 to 40 ppm) for each patient, intraindividual dose titration was performed according to a standardized protocol. In 7 consecutive male patients (mean age 56 years, range 23 to 71 years) presenting with severe RVF postoperatively, a highly significant dose-dependent and persistant decrease of pulmonary vascular resistance (PVR) could be demonstrated shortly after initiation of NO therapy without influencing systemic vascular resistance (PVR) could be demonstrated shortly after initiation of NO therapy without influencing systemic vascular resistance. Within 24 hours after initiating NO therapy, PVR fell from 338±110 to 146±51 dyn X sec X cm^{-5} ($p<0.01$) and the cardiac index rose from 2.2±0.2 to 3.4±0.5 $1/min/m^2$ ($p<0.01$). Subsequently, right ventricular function improved significantly within several days. The efficacy of NO therapy was verified every day by interrupting the NO administration for 30 minutes. During the NO-free interval a significant decrease of RVEF ($p<0.01$) and a significant increase of RVEDV ($p<0.05$) was observed. These effects as well as hemodynamic changes were fully reversible immediately after restoring the NO inhalation. As right ventricular function improved with time, the effects of NO interruption on right ventricular function gradually declined, which enabled us to wean our 7 patients off NO therapy within 2 to 14 days. Right ventricular function remained stable thereafter. In conclusion, NO inhalation is a promising new therapeutic option in the treatment of RVF after LVAD implantation and merits further evaluation.

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