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Cardiac Surgery: A Glimpse Into the Future

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The progress that has occurred in medicine during our lifetimes has been unparalleled. Forty years ago, rheumatic fever was widespread, mitral valvulotomy had not been successfully performed, the heart-lung machine had not been applied to humans and intensive care meant that the physician sat at the patient's bedside. Today, rheumatic fever has been all but eliminated, valvular heart surgery is commonplace with an operative mortality of <4%, the heart-lung machine is used in over one quarter of a million patients each year and our intensive care units, with their sophisticated monitoring apparatus, are showplaces of modern technology as applied to medicine. Although day to day progress by medical scientists occurred slowly, the overall effect produced by our unique blend of academic medicine, industry and the practitioner has resulted in a level of progress that no Solomon could have predicted.

Advances in cardiac surgery have occurred through so many routes that future directions are very difficult to predict. The dedicated clinician-scientist tackles a recognized problem, a surgeon changes the format of an operation, an industrial laboratory focuses money and personnel; each approach appears to have an even chance of advancing our field. The most we can accomplish in our review is to indicate areas in which research effort is being expended and areas in which advances in our abilities would have a favorable impact on patient care.

Vascular Surgery

Prosthetic grafts. The recognition that inert fabric tubes could serve as blood vessel substitutes provided a range of therapeutic options for patients with vascular disease (1). The use of prosthetic grafts evolved along with the specialty of vascular surgery. Modifications to encourage uniform tissue ingrowth, low initial porosity and external supports to prevent buckling have been secondary improvements that have been readily incorporated into clinical surgery.

When fabric grafts are used in vessel sizes of <10 mm in diameter the patency rate decreases to unacceptable values when compared with the rate obtained with the use of the reversed autogenous saphenous vein. A variety of treated biologic vessels have been used but, thus far, initial enthusiasm has been counteracted by premature degeneration. The development of microporous polytetrafluorethylene (PTFE) grafts has resulted in an off the shelf prosthesis that provides acceptable results in the 6 to 10 mm range when autogenous vein is not available or its use is inadvisable (2).

The need for a small vessel prosthesis (<6 mm in diameter) has been recognized for ≥2 decades. Although there is no shortage of scientific articles indicating the accomplishment of this task, no small vessel prosthesis is available when a graft is required for a specific clinical application (3–4). Despite the general recognition that the availability of a small vessel prosthesis would have a major clinical impact and that fortunes are to be made from the development of such a graft, no satisfactory prosthesis is forthcoming. A better understanding of the phenomena that occur at the anastomotic sites, new knowledge regarding the relative advantages and disadvantages of a porous versus a non-

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This article is part of a series of articles celebrating the 40th anniversary of the American College of Cardiology. The series attempts to set the stage for the future by describing current state of the art management of selected major cardiovascular problems and the basic knowledge that will provide directions for advances in diagnosis and therapy.

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porous prosthesis wall and, possibly, improved materials will play a role in this development. Although the saphenous vein is a "friend" of the vascular surgeon, there are many instances in which it is not available or should be left alone, an autogenous artery is not sufficient and a commercial prosthesis, sized for the task at hand, should be used.

Techniques for blood vessel anastomosis. The potential usefulness of rapid techniques for blood vessel anastomoses have been recognized for decades. The Soviet blood vessel stapling device rekindled an interest in non-suture techniques (5). Vascular staplers work satisfactorily if there is reasonable access to the vessels, adequate cuff lengths and minimal atherosclerosis. When these criteria are not met, most surgeons find it quicker to perform a conventional suture anastomosis. However, the successful application of the sutureless blood vessel connector has been very helpful in simplifying the repair of aneurysms of the thoracic aorta (6). Similar techniques will be applied to other blood vessels with advantage. Other options of rapid blood vessel anastomoses that have promise include the use of tissue adhesives and laser welding (7,8).

Laser techniques. The availability of laser techniques will increase the therapeutic options in vascular surgery (8). Laser angioscopy will allow visualization of stenotic lesions and will permit the surgeon to decide on the pros and cons of angioplasty techniques (dilation versus laser ablation) versus direct surgical approaches. Blind vascular procedures will no longer be performed. Moreover, for vessels in which direct dilation is the treatment of choice, but in which restenosis is a distinct possibility, a thin-walled, mesh type, metal stent will be inserted intravascularly to obviate this possibility (9).

Cardiopulmonary Bypass

Heparin anticoagulation. The availability of heparin was crucial to the development of the heart-lung machine. Commercial heparin remains a complex biologic chemical, extracted from slaughterhouse animals and composed of a mixture of mucopolysaccharides of varying anticoagulant. A single compound having uniform activity, no antigenicity and no effect on platelets will improve our ability to achieve anticoagulation during cardiopulmonary bypass and then completely reverse the effect of the drug (10). Of possibly greater importance will be the availability of a heparin antagonist that does not have the allergenic effects or the cardiovascular effects of biologically derived protamine (11).

Modern membrane oxygenators without heparin. The ability to perform cardiopulmonary bypass without heparin would simplify certain open heart operations, decrease operating time and reduce blood loss and transfusion requirements. At present, the thoracic aorta can be bypassed with use of left atrial to aortic pumping without heparin (12). Shed blood is heparinized as it is sucked from the operative field. The advantages of such a system are clear. The major element in a pump oxygenator, in which clotting occurs if inadequate heparin is present, is the oxygenator. Modern membrane oxygenators are now making their mark in cardiac surgery; their modification to prevent activation of coagulation without the use of systemic heparin will represent another major advance.

Agents to prevent platelet sequestration and activation. Platelets are sequestered in the liver during cardiopulmonary bypass and those that are available after bypass may not be capable of participating in the formation of platelet plugs. Congeners of prostacycline are now being studied that may significantly reduce sequestration and activation of the platelet during cardiopulmonary bypass (13). Again, the appropriate use of such pharmacologic agents will result in the reestablishment of normal coagulation mechanisms immediately after the completion of cardiopulmonary bypass.

Percutaneous cardiopulmonary bypass. The availability of percutaneous techniques to initiate cardiopulmonary bypass will mean that such bypass will be used to advantage as a resuscitation tool, with strict guidelines regarding indications for use, and as a circulatory support tool for patients undergoing intracardiac (valvular) or coronary artery manipulation (14,15). In the emergency situation, the benefit of the prompt institution of percutaneous cardiopulmonary support will be as apparent as are the advantages of the percutaneous intraaortic balloon.

Congenital Heart Disease

Advances in membrane oxygenation, myocardial protection and ventricular assist pumps. Over the past 2 decades, the thrust toward primary definitive repair early in life has required increasing sophistication in anesthetic management, cardiopulmonary bypass and circulatory arrest techniques and postoperative intensive care. Further advances with more efficient membrane oxygenation requiring smaller priming volume are still needed and are currently in development. Myocardial protection in the neonate has been shown to be quite different from that in the mature myocardium (16). Although basically more resistant to ischemia, neonatal myocardium is not protected by multidose cardioplegia with use of St. Thomas Hospital solution as is the adult heart (17). This metabolic riddle, possibly related to calcium flux, will be resolved, providing improved myocardial protection allowing longer aortic cross-clamp times and thus more time for intracardiac repair of complex defects. The use of extracorporeal membrane oxygenation for complete cardiopulmonary support has been successful in neonates with reversible lung disease and in pediatric patients with acute cardiorespiratory failure after repair of cardiac

defects (18). Ventricular assist pumps for infants and children are under development and should be ready for clinical trials within the next 2 years. This pump will be of great benefit not only in the management of postoperative low cardiac output but as a bridge to transplantation in infants requiring cardiac substitution. These ventricular assist pumps may also be of immense help in the management of postoperative right ventricular failure so common after repair of congenital cardiac lesions.

Tetralogy of Fallot repair. Although some advocate complete repair of tetralogy of Fallot in neonates (19), most recommend a modified Blalock-Taussig shunt in the first 6 months of life in view of the higher mortality for the single stage approach (20). With surgical experience, improved cardiopulmonary bypass and other support techniques, neonatal repair will become more universal.

The arterial switch operation for transposition of the great arteries in neonates. This operation has shown great promise and the operative mortality has continued to decrease (21). Shortly, the mortality rate will undoubtedly fall to the 2 to 3% level now associated with the overall less satisfactory atrial redirection operation, which in long-term follow-up has been associated with arrhythmia and right ventricular dysfunction.

Atrioventricular septal defects and pulmonary hypertension. Results of operations for complete atrioventricular septal defect have vastly improved as we have gained a better understanding of the cardiac anatomy of this complex defect (22). Further understanding of the complexities of the pathophysiology of pulmonary hypertension in these babies is, however, required to master the problems associated with repair of atrioventricular septal defects and other intracardiac lesions. Repair earlier in infancy eliminates some of the problems with long-standing pulmonary artery hypertension. In addition, improved ventilators and drugs specifically acting on the pulmonary circulation will be developed.

Tricuspid atresia and univentricular and hypoplastic heart syndrome. The dramatic results achieved with the modified Fontan procedure now allow not only excellent palliation in tricuspid atresia but many other complex lesions such as univentricle (double inlet right ventricle, double inlet left ventricle) heterotaxy syndrome and even the hypoplastic left heart syndrome (23). Further refinements in preoperative assessment, surgical techniques and support systems will enhance the results in the repair of these lesions (24–27).

The argument for cardiac transplantation in the hypoplastic left heart syndrome is a persuasive one: 19 of 22 infants have survived (28). However, the lack of donors and the high attrition rate of these infants while awaiting a suitable donor result in a final overall outcome not unlike that for the two stage Norwood procedure (29).

Coarctation of the aorta. Repair of coarctation of the aorta in the future will be done during the 1st year of life even in asymptomatic infants to avoid the serious late sequelae so common after repair in older children. The use of absorbable sutures and the subclavian flap procedure in infants provide immediate postoperative results almost comparable with those in older children (30,31). Further refinement in techniques will eliminate the small number of recurrences (3%). Repair of the associated intracardiac defects has been a major challenge but, as the repair of these defects without coarctation improves, a similar improvement will be seen when they are associated with coarctation.

Interrupted aortic arch remains a challenge. Better support techniques will make a one stage repair of the arch, as well as closure of the ventricular septal defect, the operation of choice with good immediate and long-term results (32).

Therefore, the number of congenital cardiac lesions not amenable to operative repair has rapidly declined to a point where almost all lesions can be either repaired or palliated. The future will bring greatly improved immediate and long-term results.

Cardiac Valve Prostheses

Mechanical versus biologic prosthesis. The first cardiac valve to be successfully implanted in a patient was of the ball-in-cage type (33). Valves of this type, albeit with minor but important changes, are being used today as state-of-the-art mechanical prostheses. Several types of tilting disc valves which have certain advantages over the ball-in-cage prosthesis, are also available. In some valves, inert, highly polished pyrolytic carbon has replaced inert, highly polished metal. All mechanical valves now available have excellent durability, but the patients require continuous anticoagulant therapy with warfarin to minimize thromboembolism. The balance between bleeding and thrombus formation is a delicate one and requires periodic prothrombin time determinations for the life of the patient. The use of glutaraldehyde-fixed biologic valves brought the hope that the incidence of valve-related thromboembolism would be reduced and that, at least in certain instances, anticoagulant therapy would no longer be required. As these hopes have materialized, gradual, progressive valve degeneration has occurred (34). Deterioration results in a need to replace a bioprosthesis, frequently in elderly patients, and has led surgeons to reevaluate their use of fixed tissue valves. Accordingly the pendulum is currently swinging toward the use of mechanical prosthetic valves in most patients, even those into their 70s, a group for whom tissue valves were previously reserved.

Unfortunately, research activity to develop improved heart valves in the United States has declined to new

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lows because of a scarcity of really good, new ideas, the tremendous costs, the long time frame associated with obtaining Food and Drug Administration approval and concern for the potential liability associated with any maloccurrence.

Aortic valve homografts. The use of stored aortic valve homografts has offered some hope and, if reported results indicating good, long-functioning life are confirmed, many more of these valves will be used in the future in the aortic location (35). The logistics of obtaining sterile cadaver valves and the additional complexity of insertion mean that the homograft valve will not qualify as the elusive ideal valvular prosthesis.

Polyurethane trileaflet valve prosthesis. Manufactured frame-mounted trileaflet valves have many desirable features, but the material design combinations evaluated thus far have not resulted in a clinically useful prosthesis (36,37). It is hoped that a better understanding of the valve mechanics, improved design using sewing rings that become incorporated into the valve annulus and the use of thin, inert, flexible polymer leaflets will result in a manufactured valve, suitable for any location, that does not require anticoagulant therapy and has a functional lifetime measured in decades.

Coronary Artery Surgery

Internal mammary artery versus saphenous vein grafts. Few areas in contemporary medicine have been the subject of as much debate as the role of surgery in the treatment of coronary artery disease. As coronary artery surgery enters its 3rd decade, there continues to be more frequent use of both internal mammary arteries, thereby reducing the need to use the saphenous vein for coronary artery grafting (38,39). The superior long-term patency of the internal mammary artery when compared with saphenous vein graft will provide improved survival, reduced cardiac-related morbidity and a decreased need for reoperation (40–42).

Changing characteristics of surgical candidates. Unfortunately, operative mortality and morbidity rates for coronary artery bypass grafting are likely to increase. This increase is and will be related to major changes in the baseline characteristics of patients undergoing the operation. Clearly, the surgical population will continue to consist of a subset with a high incidence of advanced age, severe coronary artery disease, left ventricular dysfunction and multiple concomitant medical problems (43). Additionally, urgent procedures will probably continue to increase in frequency, in many cases after other therapeutic interventions, such as thrombolysis and percutaneous transluminal angioplasty have been performed (44–47). In contrast, exciting new developments in myocardial protection and salvage and the use of devices designed for intra-arterial application will help the surgeon improve the aspects of coronary artery surgery not related to the surgeon's patient selection. This future use of improved myocardial protection and high technology, including lasers and angioscopes, may allow the surgeon to deal more effectively with severe, diffuse coronary artery disease and with patients who have impaired ventricular function.

Coronary angioscopy. Direct visual examination of the interior surface of intact human coronary arteries is now a reality (48,49). Certainly, it will prove to be a valuable research application in characterizing the atherosclerotic process. However, the most important future surgical application lies in its potential use as an adjunct to intraoperative angioplasty, thus allowing more suitable revascularization in patients with diffuse coronary artery disease. Additionally, technical anastomotic misadventures may be visualized and corrected, leading to improved graft patency (50).

Laser ablation of atherosclerotic plaques. Manual coronary endarterectomy to deal with diffuse coronary artery disease has not gained widespread acceptance in the United States because its safety and durability have been questioned (51). The laser can vaporize calcific plaques in a partially or totally obstructed artery making it a potentially useful tool to treat totally occluded as well as diffusely narrowed vessels (52). Apparently, laser surgery of normal and atherosclerotic arteries results in a scar that heals quickly with a new endothelial covering (53). For laser systems to become useful for ablation of atherosclerotic plaque, they must have little effect on normal tissue to minimize risk of perforation. At present "hot tip" (argon or YAG), excimer or "cold" and carbon dioxide lasers are under investigation. With each, the investigator must find the proper power and time of exposure to allow selective ablation without perforation or damage to normal structures. Advances and development of exogenous chromophores to detect fluorescent plaque will enable the laser system to spectroscopically recognize and distinguish atheroma and normal arterial wall and may assist in preventing perforation or vessel damage (54,55).

In the operating room, open laser endarterectomy may provide precise control over the plane of dissection. Heat sealing the surface and end points of dissection may be a potential improvement over the conventional manual surgical techniques (56). Eventually, these techniques may be possible percutaneously. Laser welding of small vessel anastomoses in which low-laser energy is applied to opposed vessel edges may prove quicker and superior to conventional suturing techniques (57). These anastomoses show no suture foreign body reaction, and neointimal hyperplasia may be reduced (58). These characteristics may enhance the patency of these small vessel anastomoses.

Myocardial Protection and Salvage

Newer techniques to preserve myocardial structure and prevent ischemic damage. The quest for the optimal alchemy of cardioplegic solutions will continue. As the mechanism of reperfusion injury is unlocked, appropriate pharmacologic additives will scavenge or inhibit production of oxygen free radicals, block intracellular calcium influx, favorably change the balance between prostacyclin and thromboxane and inhibit lipolysis to afford additional myocardial protection and limit ischemic damage (59). Other changes in the composition of the reperfusate in an effort to provide substrate for adenosine triphosphate (ATP) production may prove pivotal in preserving myocardial structure and function after periods of ischemia (60). Further insights into the conditions of reperfusion are certain to evolve as laboratory findings, indicating the critical importance of decompressing the left ventricle and gentle reperfusion, are applied in clinical trials and compared with current techniques of thrombolytic therapy with or without angioplasty in the acute setting of ischemia (61,62).

Retrograde coronary sinus infusion. Obviously, myocardial protection cannot be separated from its methodology. The role of retrograde infusion of cardioplegia through the coronary sinus as well as other coronary sinus interventions will unravel (63,64). This complex area of myocardial protection will continue to be an area of fruitful investigation, and certainly methodology first applied in the operating room will be found useful in the percutaneous route to assist the invasive cardiologist in certain acute ischemic settings.

Arrhythmia Surgery

Cardiac pacemakers. More than 50 years ago, an artificial external pacemaker and bipolar leads were designed and used successfully in patients. From these crude beginnings, change in the field of cardiac stimulation has been so rapid that the future becomes the past. Soon, most pacemakers will be dual chamber devices as small as, if not smaller than, present day single chamber units and will have similar longevity and programmable features. A single implantable unit will have a multiplicity of antitachycardia modes and even permit automatic defibrillation. It is conceivable that units designed for defibrillation will no longer require thoracotomy for defibrillator lead placement (65). Physiologic sensors will be developed to permit autoregulation of the pacemaker to maintain optimal hemodynamics. Transtelephonic monitoring systems will be developed to fully interrogate and even reprogram devices. These pacemakers will be capable of data acquisition and storage and allow serial electrophysiologic testing to assess a given therapeutic regimen (66). The technologic advances in this area appear limited only by our investigative and capital resources.

Direct arrhythmia surgery. Such surgery is now entering its 3rd decade and is well established for certain patients with refractory supraventricular and ventricular arrhythmias. Surgical division of accessory pathways in the Wolff-Parkinson-White syndrome is associated with minimal risk and excellent results (67). Clinical trials in the future will define the superiority or equality of endocardial versus epicardial closed heart approaches.

Supraventricular tachyarrhythmias. Although atrioventricular (AV) node reentrant tachycardia has been approached in a variety of ways, most entailed His bundle ablation coupled with permanent pacer implantation. Recent experience (68) indicates that this syndrome may be effectively treated by discrete cryosurgical lesions placed about the borders of the AV node. Future clinical experience may allow a closed heart technique and ultimately even a percutaneous technique. Although computerized mapping techniques are not necessary to obtain optimal results in the previously discussed conditions, mapping originally developed for use in ventricular tachycardia surgery may allow detailed electrophysiologic study of the atrium during automatic atrial tachycardias as well as atrial fibrillation and flutter. If the arrhythmia can be mapped, then a surgical technique to ablate it can be developed. Already, left and right atrial isolation procedures as well as local procedures for refractory atrial tachycardias have been employed successfully (69–71). Certainly, with future understanding and technical developments, wider applications will result. We have previously ignored the potential role of surgery in the most common of supraventricular tachyarrthymias, atrial fibrillation. This rhythm, which causes 10% of all strokes (~50,000/year) will certainly come under surgical scrutiny (72). Surgical techniques will develop to nullify both the embolic potential and the hemodynamic consequences of atrial fibrillation by preserving a normal sinus mechanism.

Ventricular tachyarrhythmias. Direct surgical techniques for the therapy of medically refractory ischemic ventricular tachycardia have been in clinical use for a decade. However, this cumulative experience would indicate high operative mortalities as well as high postoperative rates of reinducibility (73–79). These experiences would suggest that properly performed procedures to exercise or exclude a focus guided by proper intraoperative mapping reduces a postoperative reinducibility (80,81). With the future development of intraoperative mapping systems that can simultaneously record endocardial data from multiple sites without opening the ventricle, many of the current difficulties will be overcome and results will surely improve (82,83). Great advances in computer technology will allow the manufacture and widespread availability of such a system at reasonable cost. Nonetheless, patient selection will need to improve to ex-

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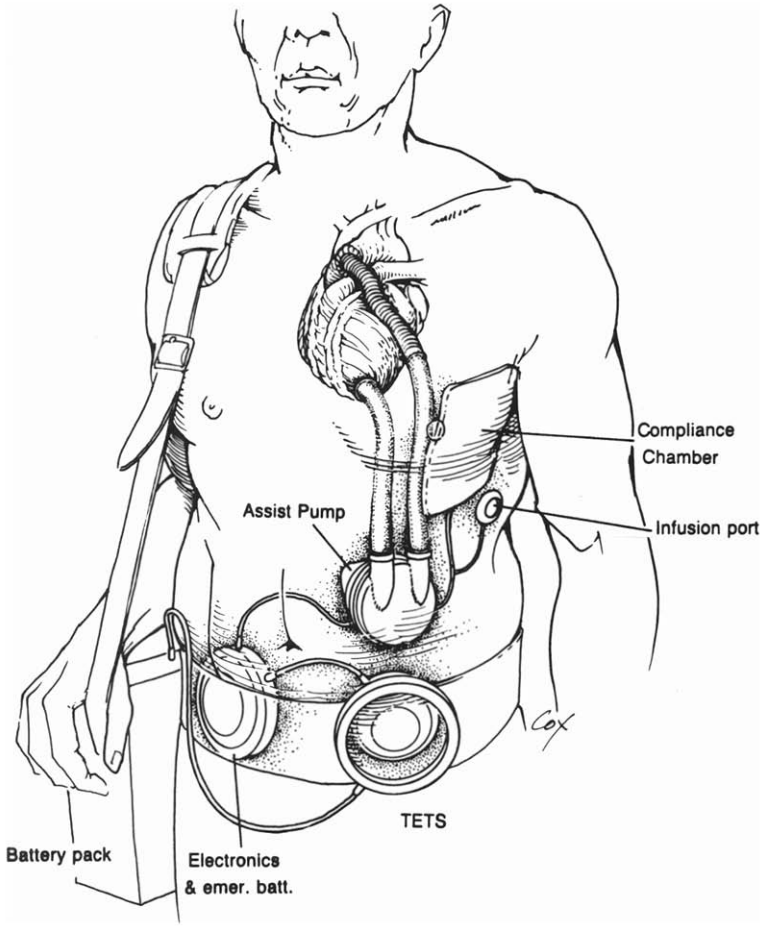

Figure 1. Proposed placement of the permanent left ventricular assist pump. The pump is positioned in the preperitoneal space in the abdomen, fills from the left ventricular apex and ejects into the ascending aorta. The energy is provided by a battery pack and is transmitted through the skin by a transcutaneous energy transmission system (TETS). The electronic control system, emergency battery (emer. batt.) pack and air system (infusion port and compliance chamber) are necessary components.

clude those patients with concomitant disease or poor left ventricular function. With the expected improvement in automatic internal cardiodefibrillators (AICD), ventricular tachycardia surgery will be performed in appropriately selected patients, achieving cure, and AICDs will be implanted for palliation in the others. The role of additional protection

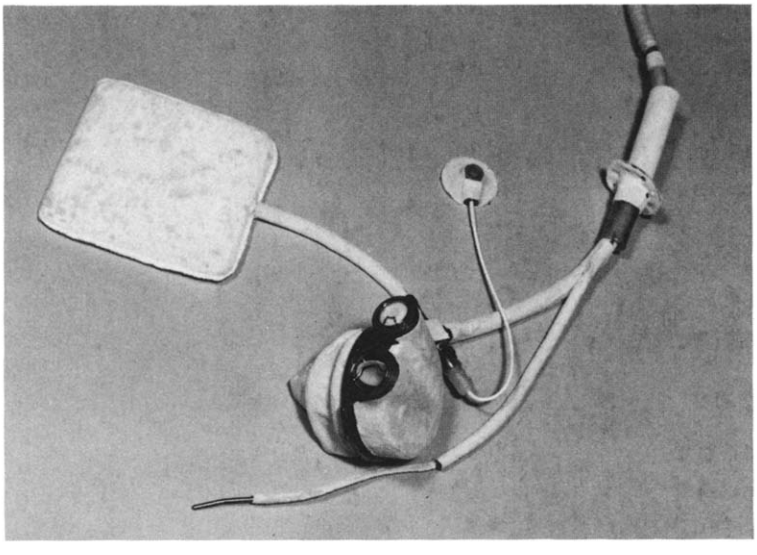

Figure 2. Prototype of the permanent left ventricular assist system that is being developed at The Pennsylvania State University. The miniature blood pump with Björk-Shiley valves is seen in the center of the photograph. Currently, this pump is energized by wires crossing the chest wall (**right**). Other components include an infusion port (**top, center**), a compliance chamber (**left**) and a thermistor probe (**lower left**). Left ventricular assist pumps have been used in animal studies for >6 month periods.

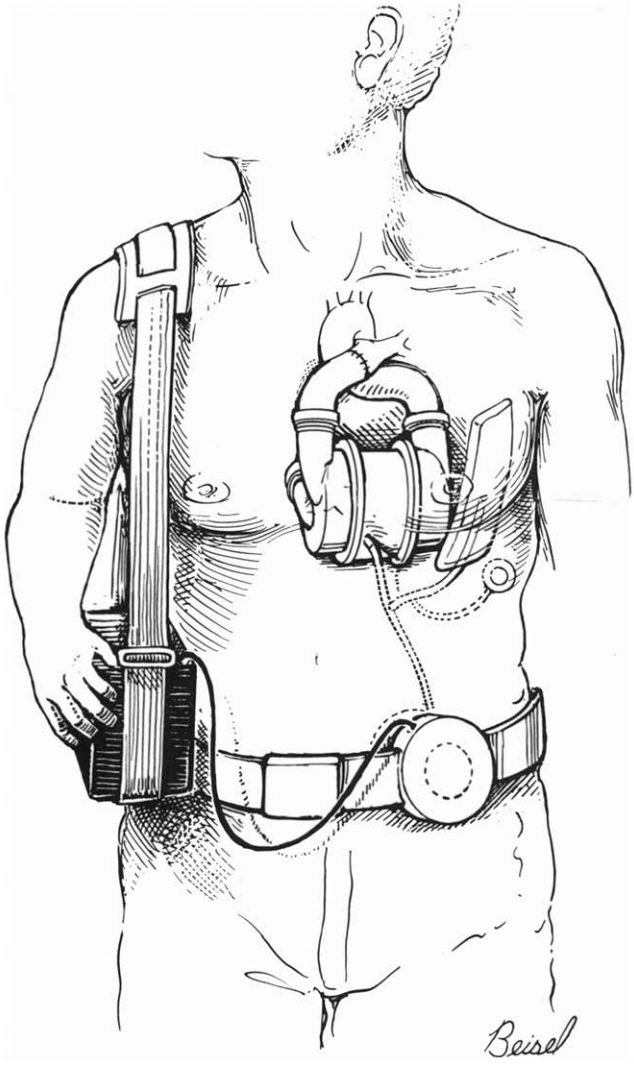

Figure 3. Proposed placement of an electric artificial heart within the thorax. To obviate the problems of percutaneous tubes, the design will employ a transcutaneous energy transmission system with the primary coil positioned with use of a belt. The patient will carry a case containing chargeable batteries.

of concomitant AICD implantation after directed surgery will surely be defined more clearly (84). Additional advances in the conduct of these direct surgical therapies will combine excision with laser or cryoablative techniques, or both (85,86).

Transplantation

Donor heart availability and preservation. Cardiac transplantation will continue to be an important therapeutic modality for patients with end-stage heart disease. Because the profession and the lay public will be better informed regarding the usefulness of donor organs, fewer potential donor organs will be wasted. However, enforced occupational and vehicular safety rules will further limit the number of trauma deaths and thus the availability of donor organs. The need for donor organs will exceed the availability by a factor of 10. Because permanent support devices and artificial hearts will be shelf items, triage will occur with the younger, better risk patients having the transplant and the older patient having the mechanical device.

Techniques for long-term (i.e., >24 h) preservation of the heart will allow the transplant to be performed in a more efficient manner and will allow country-wide and even worldwide organ sharing (87). These techniques will also be helpful in increasing the number of available donor organs. The idea of using animal hearts to replace the deceased human heart is not new; major advances in immunology will be required and would have major implications throughout the field of transplantation.

Lung transplantation. Unilateral and bilateral lung transplantation will be useful therapeutic techniques because of a better understanding of anastomotic techniques and the availability of improved immunosuppressive therapy (88). Improved preservation techniques will allow distant organ procurement and organ storage and, accordingly, will increase the availability of lungs suitable for transplantation. The use of combined heart-lung transplantation will seldom be required.

Organ selection. Immunosuppressive drug programs will be organ selective, donor antigen specific, and, accordingly, will minimize systemic side effects such as Cushing's syndrome and bulemia. The need for donor organ biopsy to define rejection and to monitor immunotherapy limits the organ recipient to living near medical centers and adds to the medical costs. Better techniques will be identified that will decrease or eliminate the need for organ biopsy and permit patient follow-up without necessitating hospitalization. Current candidate studies include echocardiography, nuclear magnetic resonance spectroscopy, detection of characteristics of circulating white cells or detection of changes in antibody levels in peripheral blood (89). Clearly, this is a current topic of great interest and importance.

Mechanical Circulatory Support and the Artificial Heart

The end result of a variety of forms of heart disease is irreversible left ventricle muscle damage. No currently known technique can restore contractile force. Cardiac transplantation offers the only available hope but is not readily available; it is costly and the long-term results are a compromise. The use of skeletal muscle to replace areas of cardiac muscle or support devices or the use of blood pumps powered by such muscle or by conventional power provides potential alternatives.

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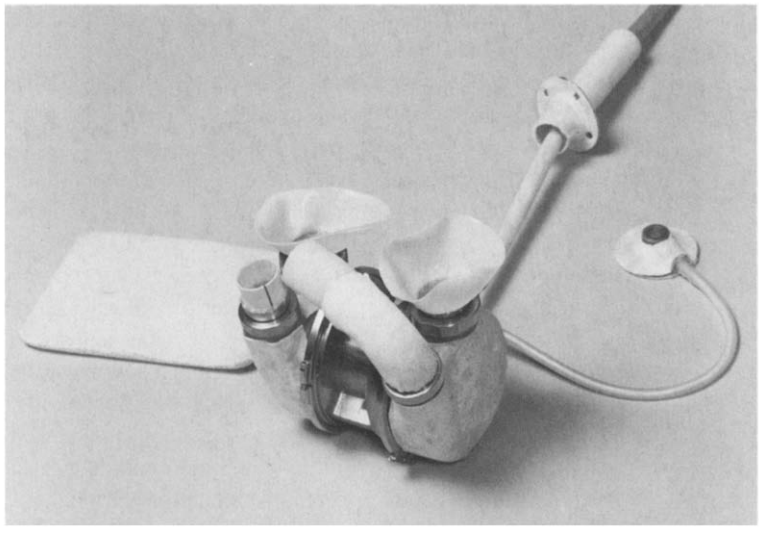

Figure 4. Prototype of the electric artificial heart. The two valved ventricles are positioned at the end of the electric motor-motion translator unit. Also shown is the percutaneous wire and the air system (compliance chamber and air port). A heart of this type has been used for >7 months in an experimental animal.

Skeletal muscle cardiomyoplasty. After the development of techniques to make skeletal muscle fatigue resistant, many investigations have begun to develop and evaluate techniques to wrap or incorporate skeletal muscle strips into the damaged left ventricle (90). Alternatively, some type of counterpulsation apparatus or blood pump can be powered by such a preconditioned muscle (91,92). The use of skeletal muscle to provide augmentation of the cardiac muscle has a definite advantage over the mechanical cardiac assist devices currently under development in that no external power source is required, although the energy available through muscle contraction is limited. Therefore, major circulatory support by such a biologic system seems unlikely. Accordingly, patients who require a 15% to 20% augmentation in cardiac output may benefit from some variant of cardiomyoplasty, whereas patients who require a greater degree of support or who require exercise ability will be candidates for transplantation or an implanted blood pump.

Ventricular assist devices. Within the next several years, implantable left ventricular assist pumps for permanent circulatory support will undergo clinical trials (Fig. 1) (93,94). These blood pumps will be used in patients who are not eligible for cardiac transplantation by virtue of age, contraindication to transplantation (insulin-dependent diabetes, for example) or lack of availability of a donor heart at the time of need. Permanent left ventricular assist pump system features include an implantable, valved, pulsatile pump and a miniature, electrically powered prime mover in the form of a rotary solenoid or brushless direct current motor (Fig. 2). The electrical energy required (12 to 18 W) will be provided by conventional house supply or by a rechargeable battery pack that can be carried and will be transmitted across the chest wall by inductive coupling (transformer principle) techniques, obviating the need for a wire or tube to cross the chest wall and reducing the risk of infection associated with percutaneous access sites. Patients with these blood pumps will require anticoagulant therapy and will have the added inconvenience of the external electrical source.

The original design features for an implantable ventricular assist pump incorporated an implantable thermal energy source (plutonium-238) and a compact external combustion (Stirling cycle) engine (95). However, the high cost of the plutonium and the risks associated with the radionuclide (two major nuclear reactor accidents have occurred in the 1980s) have led to a virtual standstill in this design. Alternatively, the major advances in permanent magnets and in the availability of microprocessors have made the completely electrical system even more practical.

Implantable artificial heart. An implantable artificial heart will be available for patients with biventricular failure in whom a transplant cannot be performed and in those in whom univentricular support is inappropriate (Fig. 3). The artificial heart that will be available at the turn of the century will have a distinct advantage over the pneumatic devices used for Dr. Barney Clark (96). The electrical devices under development obviate the need for percutaneous pneumatic power lines and, in place of the bulky pneumatic power unit, have a highly portable battery pack (Fig. 4) (97,98). Again the electrical energy will be transmitted across the skin with use of wireless techniques. At present, prototype systems are designed, suitable control techniques are available and animal implant studies are in progress. One animal has been supported for 7 months with an artificial heart of this type (although hard wire electrical transmission was used) (99).

Although these implanted pumps will be designated as permanent devices, they will have a definite functional life, analogous to that of a pacemaker. The first implantable pumps will have a proved functional life from 1 to 2 years. Periodic noninvasive parameter checks will indicate impending device failure (increased power consumption, abnormal

noise, for example) and the need for device replacement. Premature failure may also occur. In the patient with the implanted assist device, such a failure will not be catastrophic because the patient's own heart will be capable of some degree of circulatory support. Although safety circuits will be included in the implantable artificial hearts, complete backup systems will not be available because of the limited space within the chest. However, because the artificial heart will come to clinical use after the assist device, many of the premature failure modes will have been studied and eliminated.

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