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Surgical advances in heart and lung transplantation

Eric E. Roselli, MD*, Nicholas G. Smedira, MD

Department of Thoracic and Cardiovascular Surgery, Cleveland Clinic Foundation, Desk F25, 9500 Euclid Avenue, Cleveland, OH 44195, USA

The first heart transplants were performed in dogs by Alexis Carrel and Charles Guthrie in 1905, but it was not until the 1950s that attempts at human orthotopic heart transplant were reported. Several obstacles, including a clear definition of brain death, adequate organ preservation, control of rejection, and an easily reproducible method of implantation, slowed progress. Eventually, the first successful human to human orthotopic heart transplant was performed by Christian Barnard in South Africa in 1967 [1].

Poor healing of bronchial anastomoses hindered early progress in lung transplantation, first reported in 1963 [2]. The first successful transplant of heart and both lungs was accomplished at Stanford University School of Medicine (Stanford, CA) in 1981 [3]. The introduction of cyclosporine to immunosuppression protocols, with lower doses of steroids, led to the first successful isolated lung transplant, performed at Toronto General Hospital in 1983 [4]. Since these early successes at thoracic transplantation, great progress has been made in the care of patients with end-stage heart and lung disease.

Although only minor changes have occurred in surgical technique for heart and lung transplantation, the greatest changes have been in liberalizing donor criteria to expand the donor pool. This article focuses on more recent surgical advances in donor selection and management, procurement and implantation, and the impact these advances have had on patient outcome.

* Corresponding author.
E-mail address: roselle@ccf.org (E.E. Roselli).

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Donor selection

As of January 15, 2004, according to the United Network of Organ Sharing (UNOS), there were 3540 people listed for heart transplantation, 3921 for lungs, and 190 for heart-lung transplantations in the United States; yet, based on data from the International Society of Heart and Lung Transplantation (ISHLT), in 2002 only 2259 heart, 1169 lung, and 39 heart-lung patients underwent transplantation in all of North America [5,6]. The most important factor that limits use of thoracic organ transplantation for these near-death patients is the lack of availability of donor organs. In response to a short supply of organs, there has been an effort at many centers to extend criteria for donor eligibility.

Early criteria

According to conventional criteria (Table 1), acceptable heart donors were less than 50 years old and without major chest trauma or known cardiac disease. Hemodynamic instability, cardiac arrest longer than 15 minutes, conduction abnormality, acute or chronic infection with HIV, hepatitis B or C seropositivity, and systemic malignancy excluded donors. Echocardiography confirmed normal ventricular function (ejection fraction, $\geq 50\%$) and absence of valvular disease. Donors at high risk for coronary disease (hypertension, diabetes, smoking history, hyperlipidemia, and family history) and those with moderate risk who had evidence of coronary disease on catheterization were also excluded. Donors and recipients were matched to a difference of less than 20% between donor and recipient body weight [7].

Conventional criteria for lung and heart-lung donation were strict. Requirements included age less than 40, no history of lung or cardiac disease, and no history of smoking. Chest radiographic findings needed to be clear, sputum Gram stain without gram-negative organisms, and bronchoscopy findings free of purulent secretions. Again, HIV, hepatitis B or C seropositivity, or systemic malignancy precluded donation. Patients were matched by cytomegalovirus reactivity. On 100% fraction of inspired oxygen (FIO_2) and positive end-expiratory pressure (PEEP) of 5 mm Hg, the donor's partial pressure of oxygen (PAO_2) needed to exceed 400 mm Hg. Donor and recipient size matching was based on a height differential of $< 10\%$ [8,9].

Extended criteria

Age

Data from multi-institutional databases have shown that the use of hearts and lungs from donors older than age 50 increases perioperative risk compared with younger donors [10–12]. Bennet et al [13], however, used a time-dependent

Table 1
Donor selection criteria

Criteria	Early	Extended
Hearts		
Age	$\leq$ 50 y	No limit
LV dysfunction	None	Relative
Dopamine requirements	$\leq$ 10 μg/kg/min	Higher or additional inotropes
CAD	None if positive by history	Cath then PCI or CABG (rarely)
Coronary angiography	Male $\geq$ 45; female $\geq$ 50	All $\geq$ 40
Valvular disease	None	Repaired (uncommonly)
Conduction abnormality	None	Ablation or PPM
D:R weight ratio	0.8–1.2	0.6–1.5
Infection	None	Gram-positive organism treated
Hep B, Hep C, HIV serology	All negative	With exposure or consent
Ischemic time	$\leq$4 h	Up to 6 h
Lungs		
Age	$\leq$40 y	Up to 60 y
Size	Weight within 10%	Up to 40% difference
Smoking history	None	No limit
CXR	No infiltrate	Isolated infiltrate
Bronchoscopy	Clear, no aspiration or purulence	One side clear
Arterial oxygen tension[a]	$\geq$ 400 mm Hg	$\geq$ 250 mm Hg
Previous cardiopulmonary surgery	None	Acceptable
Infection	Negative gram stain	Gram-positive organisms treated
Hep B,Hep C, HIV Serology	None	With exposure or consent
Ischemic time	$\leq$4 h	Up to 8 h

Abbreviations: CABG, coronary artery bypass grafting; Cath, catheterization; CXR, chest radiograph; D:R, donor-to-recipient ratio; Hep, hepatitis; LV, left ventricular dysfunction, either ejection fraction less than 50% or hemodynamic instability; PCI, percutaneous coronary intervention; PPM, permanent pacemaker.

[a] Arterial oxygen tension: on 1.0 fraction of inspired oxygen with PEEP of 5 cm H_2O.

nonproportional hazards model to show that this risk becomes less than that of staying on the heart transplant waiting list after 64 days. With an increase in potential recipients and a time-based system for lung allocation, many lung patients are also expected to die on the waiting list. Generally, if the organ functions well, advanced age is not a limitation on organ use, and, therefore, older donors should be considered for higher risk patients.

If older organs are to be used, however, one must be aware of strong interactions between donor age and ischemic time. Similar analyses for hearts and lungs predict poor outcomes with the combination of older donors and longer ischemic times [10,12,14]; therefore, when using an older donor organ, factors such as travel time from the harvest site should be considered in estimating risk of early organ dysfunction.

In the present authors' risk analysis of 405 heart transplants performed between 1984 and 1995, we found that recipients from donors older than 50 had a

remarkable 96% 1-year survival. Although short-term results have been very good, the long-term outcomes may be diminished with older donors, that is, a 5-year survival of 60% using older donors compared with more than 70% survival in recipients of hearts from donors younger than age 50 [15]. This finding is likely the result of older donor hearts having more atherosclerosis, hypertensive heart disease, degenerative valvular disease, and possibly a greater susceptibility to chronic rejection [16,17].

Coronary disease

Expansion of the donor pool to include older patients led to an increase in the number of potential donors with coronary artery disease (CAD). Early recommendations for cardiac catheterization of potential donors included men over the age of 45 and women older than 50 [18]; however, preexisting nonocclusive CAD may predispose to an earlier development of transplantation graft vasculopathy [19]. Although significant left main or proximal left anterior descending disease precludes the use of these organs, milder disease that is amenable to percutaneous intervention or coronary artery bypass grafting may render otherwise marginal donor organs acceptable for high-risk recipients [20]. Furthermore, in a review of 1168 posttransplantation angiograms or autopsies, Grauhan et al [21] found significant ($\geq$ 50% stenosis) coronary atherosclerosis was inadvertently transmitted in 7% of all donor hearts and in 22% of the subgroup with early graft failure. Similarly, we found coronary atherosclerosis present in 56% of transplanted hearts evaluated with intravascular ultrasonography [22]. Donor age, male gender, and recipient age were independent predictors of ultrasonographically detectable atherosclerosis. We recommend screening coronary angiography in all donors over the age of 40.

Smoking history

A history of smoking used to be an absolute contraindication to donation of lungs, but the expansion of donor criteria to include those with a history of more than 20 pack years and otherwise well functioning lungs have demonstrated equivalent outcomes to nonsmoking donors. [23–25]

Cause of death

During brain death, a major aspect of the systemic response has been described as "catecholamine storm." The massive release of endogenous catecholamines leads to myocytolysis, mainly in the subendocardial region, causing a myocardial infarction-like response [26]. Donor hearts with myocardial dysfunction caused by brain death have shown reversibility after transplantation and may be selected for use with careful preoperative management (see below) and timely echocardiography [7,27]. In the early 1990s, Kron et al [28] recognized the effects of brain death on heart function as well as the risk for

aspiration and atelectasis in brain-dead lung donors. Their emphasis on inspection (of hearts to differentiate ventricular dysfunction caused by neurologic insult of brain death from intrinsic cardiac disease and of lungs to confirm that bacterial secretions and infiltrates were treatable) led to the expansion of the donor pool by 36%.

Furthermore, a comparison of head trauma with atraumatic intracerebral hemorrhage as the cause of brain death has shown a worse prognosis in those with atraumatic bleeding [11,29]. We found [29] this relationship to be especially true in HLA-sensitized patients whose survival was only 52% at 1 year with nontrauma causes of brain death compared with 93% with traumatic causes. We also found [30] spontaneous intracerebral hemorrhage in donors to be associated with an increased risk for coronary allograft vasculopathy when compared with those with traumatic brain death. These findings may be attributed to the increased prevalence of hypertensive heart disease or the activation of matrix metalloproteinases seen in donors with spontaneous intracerebral hemorrhage [30].

In the lung, the catecholamine storm associated with brain death leads to the disruption of capillary integrity and subsequent pulmonary edema, and lung donors with trauma may have associated pulmonary contusions. Furthermore, brain death and intubation increase the risk for aspiration and ventilator-related pneumonia. Multiple studies [23–25], however, have shown that lungs with mild infiltrates appearing on chest radiography may be used if donors are managed with aggressive diuresis and chest radiographs do not worsen. Similarly, lungs with arterial oxygenation tension parameters less than the commonly used limit of 300 mm Hg have been used successfully. A retrospective study [31] of 500 consecutive lung transplants at Washington University (St. Louis, Missouri) undertaken to investigate the influence of cause of donor death on outcome showed no difference in early results between donors with traumatic versus atraumatic brain injury. However, the trauma group experienced increased episodes of rejection and subsequent bronchiolitis obliterans, so these donors should be carefully considered but not excluded entirely.

Infection

All donors are tested for hepatitis B and C viruses, and transmission approaches 100% in some actively infected donors [32]. Despite this risk, a majority of lung and many heart transplant programs will accept organs from positive donors for previously exposed patients or those at high risk of dying without early transplant [32–35]. Cytomegalovirus-seropositive donors may undergo transplantation to seronegative recipients who receive prophylactic antiviral regimens with no significant effect on early outcome, but this practice may lead to chronic allograft rejection in the form of coronary graft vasculopathy or bronchiolitis obliterans [32,36].

Attempts to expand the lung donor pool by accepting those with positive Gram stains and small infiltrates observed on radiography have been largely successful [23–25], except in recipients colonized with *Burkholderia cepacia* or

multidrug-resistant organisms, because the presence of this bacterium portends poor outcome [37].

Size

For larger recipients, average size donors ($\geq$ 70 kg) may provide adequate cardiac output, despite size mismatch. Pediatric donor hearts represent another resource for expanding the donor pool. In a comparison of 14 undersized donor hearts (mean weight, 35.6 $\pm$ 7.1 kg and donor:recipient weight ratio, 0.53 $\pm$ 0.06) used for moribund patients unable to wait for conventionally size-matched hearts (mean weight, 75 $\pm$ 14.4 kg and a ratio of 0.98 $\pm$ 0.05 kg), Mather et al [38] showed echocardiographic evidence of adaptation to larger recipient circulation after 10 weeks.

Despite concerns about compressive atelectasis and cardiac tamponade, size criteria for lung transplantation have also been successfully extended for select patients. Because of increased thoracic volumes in patients with chronic obstructive pulmonary disease, patients are at little risk from oversized donors, and native lung hyperinflation after single-lung transplantation is of little consequence in both the short and long term [39]. In pulmonary fibrosis or pulmonary hypertension, patients with normal thoracic volumes, for whom oversized lungs may be more risky, partial resections to tailor donor organs to recipient thoracic space have been successfully reported with no compromise in outcome or function [40].

In summary, a number of donor variables including older donor age, CAD, smoking history, echocardiographic diffuse wall motion abnormalities, longer ischemic times, cause of death, infection, and mismatched donor size may increase transplant mortality. Because of the disparity between organ supply and demand, the length of time on the waiting list also increases mortality. When the donor organ is carefully chosen and matched against a particular patient's risk of dying on the waiting list, however, extended criteria hearts and lungs benefit a great number of patients with end-stage cardiopulmonary disease [7,23–25,41].

Donor management and procurement

Unlike other solid organ allografts, hearts and lungs must be functional immediately on reperfusion. Improved techniques of donor management and procurement aim to increase acceptable ischemic time and therefore increase the availability of organs.

In 1995, 42% of unused hearts in the UNOS database were declined because of poor ventricular function. The knowledge that ventricular dysfunction attributed to brain death may be reversible has led to further liberalizing of donor criteria to accept hearts with ventricular dysfunction and no intrinsic disease [41]. To optimize organ function and assessment, including appropriate time for echocardiography, donors may need to be monitored with pulmonary

artery catheters to guide volume status. Papworth Hospital (Cambridge, United Kingdom) increased their donor pool by 29% with the routine use of pulmonary artery catheters and hormone replacement in donors with left ventricular dysfunction [42]. Hypoxia, acidosis, anemia and hypotension should all be avoided and corrected.

In addition to the catecholamine storm, brain death causes disruption of the hypothalamus-pituitary axis. As a result, severe reductions of plasma-free triiodothyronine (T_3), cortisol, insulin and antidiuretic hormone have all been observed [26]. The thyroid hormonal profile in these brain-dead organ donors resembles that of euthyroid sick syndrome. Donor management protocols with T_3 and low-dose vasopressin infusions have demonstrated improved results [43–45]. A recent review [46] of 4543 heart transplants from UNOS compared patients receiving three-drug hormonal resuscitation consisting of a methylprednisolone bolus (15mg/kg), vasopressin (0.5–4 U/h for systemic vascular resistance 800–1200 dyne $\cdot s^{-1} \cdot cm^{-5}$) and either triiodothyronine (4 μg bolus, 3 μg/h infusion) or a single drug (L-thyroxine) for those patients who did not receive all three drugs. Those receiving the three-drug regimen demonstrated significantly improved early cardiac graft function compared with those receiving none. An insulin drip should be added to the protocol to maintain serum glucose levels between 120–180 mg/dL. The addition of hormone therapy to donor management protocols and the recognition of its ability to counteract the cardiac dysfunction associated with brain death have greatly increased the number of available donors.

Implantation: heart transplantation

Perioperative management

Many patients undergoing heart transplantation have undergone previous coronary bypass operations, left ventricular reconstruction, valve surgery, or the placement of ventricular assist devices (VAD) [47–49]. Although a great deal of experience has been gained in performing reoperations, these patients are still at risk for excessive bleeding after cardiopulmonary bypass (CPB). Although many centers routinely use aprotinin for transplantation procedures, these authors use it only in those patients undergoing VAD removal or a difficult reoperation. A test dose of 1 mL is followed by a bolus of 200 mL and then a continuous infusion at a rate of 50 mL/hour. The test dose is particularly important because many patients have been previously exposed to aprotinin, a bovine-derived serine protease inhibitor, and may be at risk for allergic reactions [50]. The risk of reexposure is debated, but the use of a test dose and withholding administration until the patient is ready to be placed on CPB may avoid the risk of anaphylaxis without a reduction in hemostatic effect [51].

As candidates for heart transplantation have become progressively sicker, a rise has also been observed in the proportion with pulmonary hypertension, a

major risk factor for morbidity and mortality caused by posttransplant right ventricular failure. Treatment strategies include the use of inotropes and vasodilators. Recently, therapy with selective pulmonary vasodilators including nitric oxide (20 ppm) and inhaled aerosolized iloprost (50 μg in 3 mL of NaCl) has been successful in reducing the risk of right ventricular dysfunction and improving survival in patients with pulmonary hypertension [52,53].

Another important risk factor is HLA mismatch between donor and recipient. Patients with high panel reactive antibody (PRA) levels and, thus, a low probability of finding a compatible donor may undergo prophylactic plasmapheresis to remove circulating antibodies, antibody-antigen complexes, and inflammatory mediators [54]. The present authors first reported successful use of prophylactic plasmapheresis in a 41-year-old woman undergoing combined heart and kidney transplantation and consider preoperative plasmapheresis in patients whose PRA levels are greater than 10% and who have substantial elevation of HLA antibodies [55].

Heart transplant operation

Advances in operative technique have been made to improve long-term outcome and quality of life. The standard technique of the heart recipient operation described by Lower et al [56] in 1960 is still preferred by some surgeons. Recipient cardiectomy is coordinated with the donor operation to limit ischemic time; longer recipient preparation times may be required for those with previous sternotomy or a ventricular assist device.

After median sternotomy and opening of the pericardium, CPB is instituted through high cannulation of the ascending aorta and bicaval venous cannulation with snares. The aorta is cross-clamped, and the right atrium is incised along the atrioventricular groove. The left atrium is opened caudally, and the two incisions are connected inferiorly. The left atrial incision is then carried left between the pulmonary veins and left atrial appendage. Large remnants of both right and left recipient atria are preserved. The aorta and pulmonary arteries are then divided at the level of the sinuses, and dissection is carried across the dome of the left atrium. The atrial septum is then divided and cardiectomy completed.

The standard technique of implantation is also known as the atrial, biatrial, or Lower and Shumway technique [56]. It begins with the left atrial anastomosis followed by right atrial anastomosis, pulmonary artery, and finally aorta. Each of the four anastomoses is performed using a single running suture.

Cardioplegia

Although perioperative management has improved, the expansion of donor criteria and high-risk recipients has allowed acute graft failure and elevated pulmonary vascular resistance to persist as major causes of early death after heart transplantation. In an attempt to improve initial recovery of transplanted hearts,

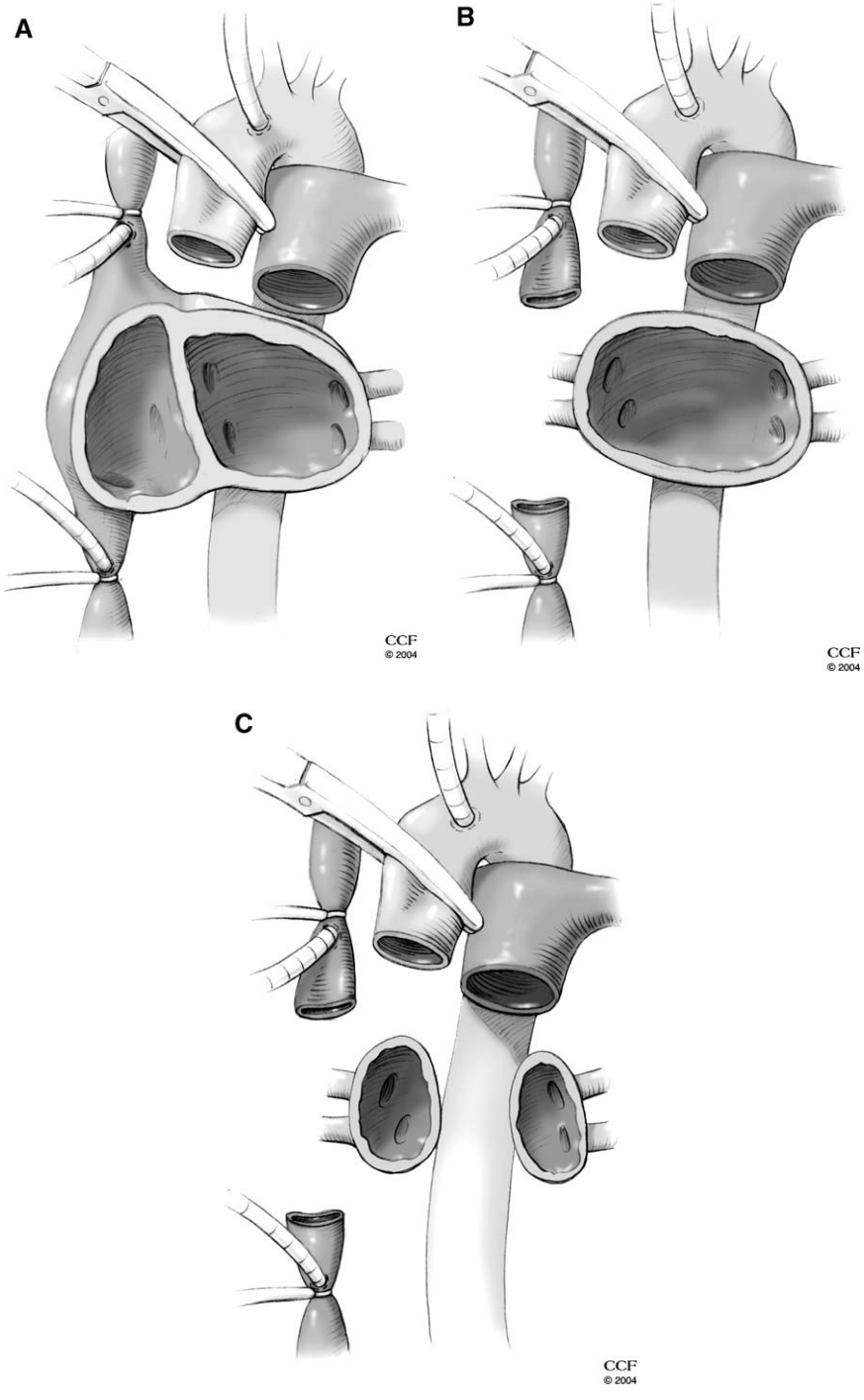
a trend toward myocardial reperfusion has been emerging [57]. Cold blood cardioplegia is now delivered before implantation and once during implantation, and then warm blood cardioplegia reperfusion is delivered just before removal of the cross clamp. Topical cooling is no longer used to minimize cold injury to the phrenic nerves.

Standard versus bicaval versus total technique

It was recognized early on that the original technique of heart transplantation led to a significant amount of arrhythmias, and one early modification extended the right atrial incision toward the appendage to reduce the incidence of sinoatrial node dysfunction. Altered atrial geometry of this mid-atrial anastomotic technique probably contributes to arrhythmias, loss of atrial contractile function, and atrioventricular valve incompetence. In response to these disadvantages, alternate operations including bicaval (5 anastomoses) and total (6 anastomoses) techniques have been developed and have gained favor in the last decade (Fig. 1) [58]. A recent survey of ISHLT centers with an 80% response rate reported that the bicaval technique has become most common for heart transplantation, with 38% of centers using it exclusively, and 68% using it in at least half of the cases. Only 13% of centers still used the standard technique exclusively, and 4.5% of centers exclusively used the total technique. The total technique, which entails two separate pulmonary venous anastomoses in addition to the bicaval and great vessel anastomoses, was shown to have a significantly longer mean time of implantation than standard or bicaval techniques, which did not differ with regard to time of implantation [59].

Several studies, including three randomized trials, [60–64] have been performed to compare the newer techniques to standard technique; however, a comparison of bicaval to total technique has not been made. Most studies [65,66] demonstrate fewer early and late postoperative arrhythmias with the newer techniques versus the standard technique, but the clinical end point of a reduction in the use of a permanent pacemaker has not been shown. Evaluation of hemodynamic parameters including atrial size and function has also yielded promising results with the bicaval and total techniques, but a comparison of overall cardiac function between the two groups has revealed mixed results. Aziz et al [59] reported better 5-year survival rates with the bicaval technique because of less right heart failure, and Aleksic et al [67] showed a possible benefit of the total technique in a subgroup of patients with pulmonary hypertension. Other groups report no difference in cardiac function.

Although the consensus among most transplant surgeons is that the preservation of more normal atrial geometry with these newer techniques is probably beneficial, the bicaval anastomosis is not without complications. Cases of superior vena cava syndrome resulting from anastomotic strictures have been reported [68]. Other minor modifications to the bicaval technique include leaving a thin strip of right atrial tissue connecting the two cavae, thus facilitating the bicaval anastomosis and preventing kinking, twisting, and subsequent stenosis [69,70]. Further investigation is necessary to confirm a difference with regard to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the theoretical advantage of decreased mitral and tricuspid regurgitation attributed to decreased atrial distortion with these bicaval techniques.

Tricuspid valve repair

Although tricuspid regurgitation may be reduced by use of a bicaval anastomosis, it remains a problem both early and late for these patients, leading to increased venous pressures, decreased myocardial function, and, if severe, the need for surgical repair or replacement [71]. Aziz et al [72] (the Wythenshawe group) found the risk factors for tricuspid regurgitation to be the use of the standard technique of implantation, the number of episodes of grade two or worse rejection, and the number of heart biopsies. A recently presented randomized trial [73] of prophylactic tricuspid annuloplasty during heart transplantation demonstrated lower early mortality and shorter reperfusion times with no procedure related stenosis or heart block.

Implantation: lung transplantation

Patient selection

Efforts to improve survival while waiting for suitable organs have led to the development of alternative therapies for advanced lung disease. Pulmonary rehabilitation programs have been shown to improve exercise tolerance and quality of life. For chronic obstructive airway disease surgical alternatives, including lung volume reduction surgery and endobronchial airway fenestration, may allow some patients to not only postpone transplantation but to defer it altogether. For pulmonary hypertension, an increased understanding of the diagnosis, indications, and surgery for chronic thromboembolic pulmonary hypertension and the expansion of pulmonary- specific vasodilatory medications (prostacyclin, sildenafil) has allowed many patients to be withdrawn from transplantation lists [74,75].

Perioperative management

For patients undergoing lung transplantation, the recipient is taken to the operating room approximately 90 minutes before the arrival of the donor organ. A double-lumen endotracheal tube is most frequently used, but bronchial blockers may be necessary in patients with smaller airways. Intravenous fluids should be limited, and PEEP should be avoided in those with obstructive lung disease.

Fig. 1. Various heart transplant techniques are shown as recipient anatomy after cardiectomy. (*A*) Standard. (*B*) Bicaval. (*C*) Total.

The ability to perform lung transplantation without the assistance of CPB requires the recipient to tolerate single-lung ventilation. Patients with pulmonary hypertension usually require CPB, and those with restrictive lung disease are more likely to need CPB than those with obstructive disease. If a patient desaturates with single-lung ventilation, occlusion of the pulmonary artery to be excised may decrease shunting and obviate the need for CPB. No evidence shows CPB affects outcome [76].

Lung transplant recipients over the age of 50 often have risk factors for coronary artery disease including smoking and obesity. Lee et al [77] described four patients who underwent concomitant coronary bypass grafting with lung transplantation, two with the assistance of CPB and two without, with excellent outcomes.

Lung transplant operation

Standard lung transplantation is performed either as a single-lung transplant or bilateral sequential transplants, which have proved to be more successful than the original double-lung transplants performed with tracheal anastomosis. For single-lung transplantation, a posterolateral thoracotomy is performed through the fourth or fifth intercostal space. Hilar mobilization of the main pulmonary artery, superior and inferior pulmonary veins, and main-stem bronchus is performed. Once the donor lung arrives, pneumonectomy is completed in standard fashion with the use of staplers. The bronchial anastomosis is performed first with a running suture along the membranous portion followed by interrupted sutures along the cartilaginous portion. The pulmonary arterial anastomosis is performed next followed by the left atrial cuff. The bronchial anastomosis is often wrapped with pericardial fat, clamps are removed, and flow reestablished. For bilateral lung transplants, a clamshell thoracotomy incision is used, the least functional lung is removed first, and the same operative technique as described above is used for both sides.

Incision type

As bilateral lung transplantation evolved from tracheal anastomosis to sequential bronchial anastomoses, the approach also changed from predominantly midline sternotomy incisions to clamshell incisions (through the fourth or fifth interspaces). The sternotomy portion of clamshell incisions, however, is prone to poor healing, with an incidence of up to 34% of sternal override and infection [78,79]. Patterson and coworkers [79] recommended bilateral anterior thoracotomies without sternal division as an alternative, but this approach can limit exposure. Lonchyna [80] suggested modification of the transverse sternotomy to an inverted V shape to improve stability. We still prefer either midline sternotomy or modifying the sternotomy portion of the clamshell incision by beveling to maintain stability without compromising access for cannulation if CPB becomes necessary.

Implantation: heart-lung transplantation

Patient selection

Indications for combined heart-lung transplantation have become restricted because of the success of isolated lung transplantation and the limited availability of donors. Even in patients with severe pulmonary hypertension and right ventricular dysfunction, lung transplantation is a very good option [81,82]. However, combined heart-lung transplantation procedure is necessary in patients with irreparable congenital cardiac lesions leading to Eisenmenger's syndrome and severe combined cardiopulmonary disease.

Heart-lung transplant operation

The patient is positioned in a supine position and intubated with a single-lumen endotracheal tube. The approach is through the median sternotomy or clamshell incision. The pericardium and pleura are opened widely, taking great care not to injure the phrenic, recurrent laryngeal, and vagus nerves. The patient is heparinized and cannulated as for heart transplantation. The aorta is cross-clamped, and cardiectomy and pneumonectomies are performed as described above once organs arrive in the operating room. Bronchial remnants are mobilized, and the trachea is divided just proximal to the carina.

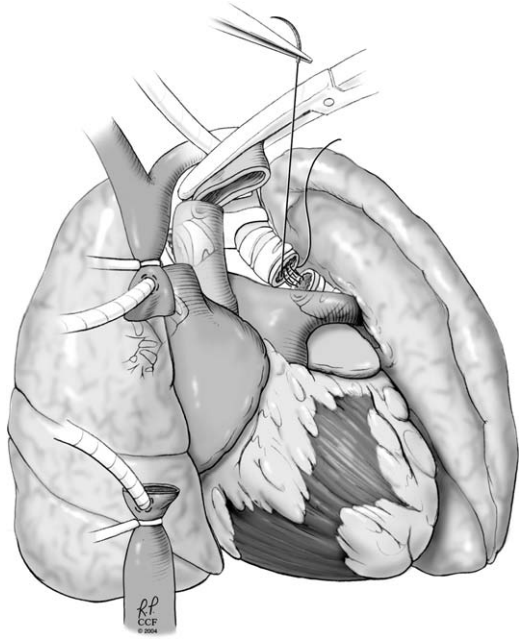

Fig. 2. Bibronchial technique of heart-lung transplantation.

The heart-lung bloc is then placed in the chest, and the lungs are passed under the phrenic nerve pericardial pedicles. Tracheal anastomosis is performed with a running suture on the membranous portion of the airway and then interrupted sutures through the cartilaginous portion. A running right atrial anastomosis is then performed followed by end-to-end aortic anastomosis. Next, an intravenous steroid bolus is delivered, the aortic vent is placed, the aortic clamp is removed, and the patient is weaned from bypass.

As described above for the right atrial anastomosis portion of heart transplant implantation, either standard biatrial or bicaval anastomosis may be performed for heart-lung implantation. The bicaval technique in these patients should confer the same advantages as it does in isolated heart transplants.

The principal reasons for early mortality in heart-lung transplant are graft failure and bleeding [83]. To reduce potential bleeding complications associated with difficult exposure, Icenogle and Copeland [84] described a technique of placing the lungs anterior to the phrenic nerves to allow less restricted exposure to the posterior atrial and tracheal anastomoses.

As an alternative to tracheal anastomosis, we use a bibronchial technique, similar to that described by Griffith and Magliato [85], to avoid potential bleeding from prominent bronchial vasculature in the posterior mediastinum around the carina and to promote airway healing, as has been observed for double-lung transplantation. This technique is performed with the patient either intubated with a double-lumen tube or a bronchial blocker. Once the heart-lung bloc is placed into the thoracic cavity, bronchial anastomoses are performed sequentially as for double-lung transplants, followed by aortic and finally bicaval anastomoses (Fig. 2).

Outcomes

In the recent era of heart transplantation, data from our institution, other single institutions, and multi-institutional reports characterize recipients as older, most

Table 2
Posttransplantation survival

	5-year survival (%) (n)	
World experience	1988–1992	1998–2001
Heart	67 (16,621)	70 (10,678)
Lung	40 (2093)	45 (4831)
Heart-lung (1982–2001)	40 (2889)	

Data from Taylor DO, Edwards LB, Mohacsi PJ, Boucek MM, Trulock EP, Keck BM, et al. The registry of the international society for heart and lung transplantation: twentieth official adult heart transplant report-2003. J Heart Lung Transplant 2003;22:616–24; and Trulock EP, Edwards LB, Taylor DO, Boucek MM, Mohacsi PJ, Keck BM, et al. The registry of the international society for heart and lung transplantation: twentieth official adult lung and heart-lung transplant report-2003. J Heart Lung Transplant 2003;22:625–35.

likely to be UNOS status-one and increasingly bridged to transplantation with VAD [86–88]. Furthermore, donors are older, ischemia times have increased with farther travel times, and more complex operations and mismatches are more common. Despite these changes, several factors no longer appear to be risks, and a progressive improvement in survival has been seen (Table 2) [88]. Similarly, lung transplant recipients are older, and total activity has expanded since 1990. Recent survival rates for lung transplantation have also significantly improved [89]. For both heart and lung transplants, the advantage in survival has been most prominent in the early phase. Similarities in the late slopes of survival curves compared across eras emphasize the need for further refinements in therapies to combat chronic rejection and extend the natural history of thoracic allografts.

Summary

Successes of thoracic transplantation have led to the expansion of indications and subsequent growth in demand for a short supply of organs. In response to this disparity, criteria for organ donation have been liberalized. Despite these difficult challenges, with advances in surgical techniques and perioperative care of both donor and recipient, outcomes have continued to improve over time.

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