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Evolution of Heart Transplantation Surgical Techniques

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Abstract

Organ transplantation has kindled the human imagination since the beginning of time. Prehistorically, transplantation appeared as mythological stories: from creatures with body parts from different species, the heart transplant between two Chinese soldiers by Pien Ch'iao, to the leg transplant by physician Saints Cosmas and Damian. By 19th century, the transplantation concept become possible by extensive contributions from scientists and clinicians whose works had taken generations. Although Alexis Carrel is known as the founding father of experimental organ transplantation, many legendary names had contributed to the experimental works of heart transplantation, including Guthrie, Mann, and Demikhov. The major contribution to experimental heart transplantation before the clinical era were made by a team lead by Richard Lower and Norman Shumway at Stanford University in the early 1960s. They played the vital role in developing experimental and clinical heart transplantation as it is known today. Using Shumway biatrial technique Christiaan Barnard started a new era of clinical heart transplantation, by performing the first in man human-to-human heart transplantation in 1967. The techniques of heart transplant have evolved since the first heart transplant. This chapter will summarize the techniques that have been used in clinical heart transplantation.

Keywords: heterotopic heart transplantation, orthotopic heart transplant, bicaval technique, biatrial technique, cardiectomy, donor heart preparation

1. Introduction

Heart transplantation has captivated the human mind since the beginning of time. Prehistorically, transplantation appeared as mythological stories with creatures whose bodies consist of parts from different species. It is possible that chimeric beings, such as the Chimera of Greek mythology with a human head, snake tail, and lion heart and body, were created surgically through supernatural forces. Many transplant mythological tales suggested a surgical basis for these myths, with the most striking story reported by a Chinese doctor Pien Ch'iao in the 4th decade B.C. when he examined two sick soldiers and made the diagnosis that each had an imbalance of Yin and Yang; one had a strong will but weak spirit, while the other had the opposite. To correct the imbalance, he anesthetized them with powerful medication and cut open their chests and exchanged their hearts. Patients were unconscious for 3 days. After waking up they felt markedly improved [1].

By the late 19th and early 20th century, the transplantation concept became possible by the development of surgical aseptic vascular anastomotic technique and understanding of the role of immunology in organ rejection. Alexis Carrel is known as the founding father of experimental organ transplantation. He was a French surgeon who developed the technique of vascular anastomosis in Lyon, France, and later he applied it to transplant a kidney into the necks of dogs [2].

Carrel left Lyons for the University of Chicago and began his collaboration with Charles Claude Guthrie. Together they established the foundation of organ transplantation using their vascular surgery technique. Their team described the first heterotopic heart transplant in mammals, where they connected a heart from a small dog into the neck of a larger one [3].

Frank C. Mann and his coworkers at the Mayo Clinic, modified the technique described by Guthrie and Carrel to create a heterotopic heart transplant in the dog neck to expand on the study of heart transplantation and make the seminal contribution to the field by describing that immunologic rejection was the main cause of graft failure. They also recognized the importance of ventricular distention and air embolism and the need for heparin to prevent thrombosis [4–6].

Vladimir Demikhov, a Russian physiologist, whose work was hidden from the west achieved a milestone in transplantation in the 1940s and 1950s. He performed a series of experimental operations on canines that includes orthotopic heart transplantation, heterotopic heart transplantation, and heart-lung transplantation in bloc [7]. In the meantime, Wilford Neptune and his group at Hahnemann Medical College in Philadelphia, performed heart-lung transplantation in dogs without cardiopulmonary bypass using hypothermia in the recipient dog [8]. The major contribution to experimental heart transplantation before the clinical era were made at Stanford in the early 1960s. Richard Lower and Norman Shumway and their team were responsible for developing heart transplantation as it is known today [9–12].

The first human heart transplant was performed with a chimpanzee donor. This was performed by Dr. James D. Hardy at the University of Mississippi Medical Center in January 1964, using Shumway technique [13]. Unfortunately, the small heart could not handle the large venous return of the recipient, and the patient died 1 hour after implantation of the heart [13].

On December 3, 1967, the first human-to-human heart transplantation took place at Groote Schuur Hospital, Cape Town, South Africa, by Christiaan Barnard and his team. They retrieved a heart from a donor after circulatory death (DCD), which is considered the first DCD heart, and implanted it into a 57-year-old patient with ischemic cardiomyopathy [14].

In today's clinical practice, orthotopic heart transplant (OHT) is the gold standard treatment for patients with refractory congestive heart failure from end stage heart diseases [15]. Many heart transplant techniques have been described. The bi-atrial technique, which was refined and popularized by Lower and Shumway in 1960 [9], was used to perform the first heart transplantation and was widely used for its relative simplicity. 'Wythenshawe' bi-caval technique of heart transplant, described by Sarsam et al. [16] had replaced the original biatrial technique in most transplant centers because it is more anatomical, associated with less sinus node dysfunction, and less tricuspid regurgitation. Yacoub and his colleagues introduced the total heart transplant technique in 1989 [17], however it did not gain much popularity because of its complexity without much physiological advantages. The heterotopic heart transplant techniques, described by Barnard in 1975 [18], was developed to treat patients with irreversible pulmonary hypertension, and as a way to keep the patient alive in

case the donor heart fails due to primary graft dysfunction or severe rejection, the main cause of death after heart transplantation before cyclosporine era. Heterotopic heart transplant is rarely used today because of the advents in left ventricular assist device and immunosuppressants. However, it is still a useful technique as a biological left ventricular assistance (a new two-stage method) for heart failure treatment some specific circumstances [19].

In this chapter we will describe evolution of heart transplant techniques that have been used for patients with normal cardiac anatomy. Various modifications of these techniques have been adapted for patients with end-stage congenital heart diseases but will not be discussed in detail.

2. Clinical heterotopic heart transplantation

After a series of experimental techniques and studies on animals [20–23], clinical heterotopic heart transplantation was introduced by Barnard and colleagues at the Groote Schuur Hospital, Cape Town, South Africa in 1974 [18] in response to a clinical need that was not met by orthotopic heart transplantation, namely, heart failure with pulmonary hypertension. Currently, heterotopic heart transplants are performed rarely but may be indicated in patients with irreversible pulmonary hypertension or significant donor-recipient size mismatch, when left ventricular assist devices are not available or contraindicated [24].

In addition, this technique could be used as a temporary bridge to recovery in patients with cardiogenic shock. The other benefit is that the circulation of a patient could be maintained in case of rejection by the native heart. Furthermore, the graft could be removed by side-clamping the three anastomotic areas without the use of cardiopulmonary bypass in the setting of rejection or recovery.

2.1 Preparation of the donor heart

The heart is prepared on the back table in a sterile field and a basin of cold normal saline or cardioplegic solution. The stump of the IVC and the orifices of both right pulmonary veins are closed with continuous 5-0 polypropylene sutures, with care not to occlude the orifice of the coronary sinus. The bridge of tissue between the left superior and inferior pulmonary veins is excised to create a single opening into the left atrium. This opening may need to be extended to achieve a diameter of approximately 3.5–4 cm, or the equivalent of a normal mitral valve orifice. The midpoint of the posterior wall of this opening is marked with a suture as a reference during subsequent implantation into the recipient. The main pulmonary artery is divided at its bifurcation to allow extra length for implantation. A longitudinal 5 cm incision, just to the right of the interatrial septum, is made in the posterior aspect of the SVC and right atrium; at least half the length of this incision must involve the right atrial wall [25].

2.2 Preparation of the recipient

With the recipient in supine position, a median sternotomy is performed, and pericardium is opened longitudinally. Then a large right rectangular pericardial window is created in the right pleural cavity to accommodate the donor heart. Care is taken to avoid damaging the right phrenic nerve.

Hemostasis of the edges of this flap must be carried out carefully because the exposure will be difficult after the heart is in place. Next patient is fully heparinized, and the recipient is cannulated with an aortic cannula inserted at the level of the origin of the innominate artery, and venous cannulas in the SVC and the IVC (through the low atrial wall). Umbilical tapes snares are placed around the SVC and IVC to achieve total cardiopulmonary bypass (CPB) at some stage of the operation. Cardiopulmonary bypass is initiated, and a left upper pulmonary vein vent introduced. The patient is cooled to 28°C and cardioplegia is given through the aortic root.

2.3 Heterotopic implantation

The donor heart is placed in the right thoracic cavity in the window created anterior to the right lung and lying as a mirror image of the recipient's heart. An incision is made into the recipient's left atrium posterior to the interatrial groove, as in the mitral valve surgery incision. The midpoint of the posterior lip of the incision in the recipient left atrium is sutured using double-ended 4-0 polypropylene to the midpoint of the posterior lip of the donor left atrium at the site of the previously inserted marker stitch. The posterior aspect is completed first then the anterior aspect. The completed anastomosis will be totally inaccessible at the end of the operation therefore, it is essential that it be hemostatic. A 5 cm longitudinal incision is made into the lateral aspect of the recipient SVC and right atrium just anterior to the interatrial groove, beginning 2–3 cm above the junction of the vena cava and extending 3 cm into the right atrium. The midpoint of the posterior lip of the incision in the recipient atrium is sutured to the most caudal point of the incision in the donor atrium, using a double-ended 5-0 polypropylene suture (**Figure 1A**). The two right atria are then anastomosed by a continuous suture proceeding in each direction like a diamond shape, first posteriorly and then anteriorly. This allows the widest possible opening and prevents kinking of the right atrial anastomosis. At the completion of this anastomosis the ligated donor azygos vein remnant will lie at the midpoint of the anterior suture line.

Heterotopic Heart Transplant Technique

Figure 1.
(a) After finishing the left atrium anastomosis, a longitudinal incision is made on the recipient right atrium anterior to the interatrial groove, and the incision is extended superiorly into the SVC. After the donor right atrium is similarly incised, the donor recipient anastomosis is performed in a diamond shape. (b) The donor aorta is anastomosed to the recipient's by end-to-side anastomosis, and the PA is connected to the right atrium appendage for left heart support. (c) For bi-ventricular support configuration, the PA is connected, via a Dacron graft the recipient's PA.

Although the atrial anastomoses can be done with the beating recipient's heart, it is easier to perform these anastomoses with the native heart in an arrested state.

The donor's aorta is trimmed to the appropriate length and anastomosed in an end-to-side fashion to the recipients. It is important to trim the donor's aorta to the minimum length required, otherwise the donor heart will drop back into the right pleural cavity and cause compression atelectasis of the right lung. The cardioplegic catheter in the donor aorta is converted for use as an air vent, and the caval snares are released. For left ventricular support alone, the donor pulmonary artery is connected to the right atrial appendage (**Figure 1B**). For biventricular support the donor's pulmonary artery is connected to the recipient's main pulmonary trunk. To do that the donor pulmonary artery has to be extended with a conduit (usually Dacron graft) to prevent undue tension or distortion of the other anastomoses. The size of graft chosen will depend largely on the diameter of the donor pulmonary artery; this is usually on the order of 22 mm. The Dacron graft is anastomosed end-to side to the recipient pulmonary artery using continuous 5-0 polypropylene suture (**Figure 1C**). After assuring that all anastomoses are hemostatic, the SVC cannula is withdrawn into the right atrium and the IVC cannula is removed. Inotropic medications are started as needed, and if the hemodynamic status is stable, cardiopulmonary bypass is discontinued and all cannulas are removed from the patient.

2.4 Modifications of the heterotopic heart transplant techniques

In 2017, Copeland et al. [26] published an alternate heterotopic heart transplant technique as a biologic left ventricular assist device. The donor heart left pulmonary veins and inferior vena cava are oversewn, like original technique. The donor and recipient left atria are anastomosed first. Then, the donor aorta is anastomosed to the recipient aorta in an end-to-side fashion. The aortic cross clamp is removed, and the patient is placed in Trendelenburg position. The donor pulmonary artery is anastomosed to the recipient right atrium. The donor superior vena cava (SVC) is anastomosed to the recipient superior vena cava in an end-to-side fashion. The anastomosis of the SVC is marked with clips to facilitate identification of the anastomosis during future endomyocardial biopsy through the right internal jugular vein.

Recently, Gaiotto et al., proposed a two-stage approach that allows conversion of a heterotopic heart transplant into an orthotopic one in patients with secondary pulmonary hypertension due to left ventricular failure [19].

The intention of this new approach is to decompress the native left ventricle to allow reversal of pulmonary hypertension, (LV) while preserving the donor's right ventricular function by diverting the entire blood volume from the SVC flowing through the donor RV. They proposed a slight modification of the Copeland technique by an end-to-end connection of the donor's and recipient's SVC; the rest of the anastomoses are the same as in Copeland's description. This first stage allows the recipient to have a biological left ventricular assist device while preserve the donor right ventricle function by filling it with blood from the upper part of the body. Because the RV is a flow-dependent chamber, its function would be preserved as it will receive all blood from the superior vena cava (SVC). This will prevent the donor RV from undergoing atrophy that is associated with the reduced blood flow from the side anastomosis of the original Copeland's technique. This modification provides decompression of the recipient LV and gradual reduction of the pulmonary vascular resistance through the parallel connection of the donor and recipient's left ventricles via the left atrial anastomosis.

When the recipient pulmonary hypertension resolves, the patient will undergo a second stage operation, in which the native heart will be removed and the donor heart will be “twisted” into the orthotopic position, connecting end-to-end the donor’s PA (via a Dacron graft extension) to the recipient PA, and anastomosing the stump of the donor’s IVC to the recipient’s IVC. The technique will obviate the associated complications from having the native heart in circulation, such as thrombus formation in the native left ventricle, needs for long-term systemic anticoagulation, and ventricular fibrillation [27, 28]. Of note is the fact that this is just a concept proposed by Gaiotto et al.; they have not reported any actual case yet. However, the concept is supported by a case report in which the native heart was removed from a heterotopic heart transplant patient with success. Pham et al. [29] first reported case of congestive heart failure due to regurgitation of the native aortic and mitral valves, causing a left-to-left shunting in a patient with a heterotopic heart transplant. The arterial blood recirculates from the ascending aorta through the incompetent native aortic and mitral valves to the native and transplanted donor left atria, then donor left ventricle causing volume overloading of the heterotopic donor heart and congestive heart failure. The patient underwent resection of the native heart and survived more than 2 years later. This case demonstrated that the heterotopic donor heart alone can sustain the recipient after pulmonary hypertension resolved.

3. Bi-atrial technique of heart transplantation

Bi-atrial heart transplant technique is the first technique used in clinical heart transplantation. Shumway and Lower at Stanford University refined this surgical technique, which later called “Shumway” or bi-atrial technique (BA) [9]; it became the standard heart transplant surgical technique until the 1990s. The Stanford group also introduced the use of cold (4°C) isotonic saline solution to preserve the donor heart and the use of cardiopulmonary bypass to support the transplanted heart temporarily after the completion of the operation to until the donor slowly took over the circulation [30].

3.1 Cardiectomy

Communication between recovery team and transplanting team is very important to reduce the ischemic time, cardiopulmonary bypass time, and unnecessary delay. Communication and timing between both teams is very critical. If the ischemic time is short, cardiectomy of recipient heart could be done when the donor heart in the operating room, or just before the donor heart arrive to the hospital.

The chest is opened in a normal fashion through median sternotomy, the pericardium is opened vertically and horizontally as reversed T shape, then a full dose of heparin is given. When the ATC level is reached above 400, then cannulation of the aorta, SVC, and IVC is performed.

Cannulation of the aorta should be high and optimal usually just proximal to the origin of brachiocephalic artery, and the CPB is initiated. Then the aorta is cross clamped the venous cannulation is snared with umbilical tapes to achieve complete CPB.

The cardiectomy starts by opening the right atrium along the atrio-ventricular groove toward and coronary sinus inferiorly and toward the roof of the left atrium (**Figure 2A**). The interatrial septum is open with a blade at the foremen ovale and extended inferiorly to the coronary sinus orifice and superiorly

Figure 2.
 Recipient's cardiectomy. (a) The recipient's cardiectomy is initiated by opening the right atrium along the atrio-ventricular groove. (b) The great vessels are transected above the semilunar commissures. (c, d), The atria are incised along the atrioventricular grooves, leaving cuffs for allograft implantation.

to the roof of the left atrium between the SCV and the root of the aorta. The great vessels are transected above the semilunar valves (**Figure 2B**). The recipient's cardiectomy is completed by continue to divide the left atrium along the atrioventricular grooves (**Figure 2C and D**). The left and right atrial cuffs are then trimmed, including removal of both atrial appendages (**Figure 2D**). Electrocautery is used to separate the proximal ends of the aorta and pulmonary artery to have a clear swing margin and to reduce the bleeding. Right pulmonary artery should be visualized to reduce damaging it during dissection. To achieve a dry field of blood a vent drain is placed at the left atrium remnant directly or through the right superior pulmonary vein.

The stumps of the recipient aorta and pulmonary artery are suspended with stay sutures to retract these structures away from the field to facilitate exposure of the left atrial cuff for anastomosis.

3.2 Donor heart preparation

The donor heart is removed from the transport cooler and placed in a basin of cold saline or cardioplegic solution at the back table. Sharp dissection is used to isolate the aorta from the PA.

The left atrium is tailored to the size of the recipient LA remnant, by connecting the left pulmonary veins orifices with the right pulmonary veins orifices and trimming the access tissues. The interatrial septum is inspected and a patent foramen ovale, if present, is closed. The SVC of the donor heart is ligated, and an incision is made in the

Bi-atrial Heart Transplant Technique

Figure 3. Bi-atrial heart transplant technique. (a) Preparation of the donor heart at the back table. (b) Recipients atrial cuffs after cardiectomy. (c) Lines of anastomoses for left and right atriums. (d) Final sutures line as seen anteriorly after completion of aortic and PA anastomoses.

posterior wall of the stump of the inferior vena cava and continued toward the SVC and directed away from the sinus node either posteriorly (**Figure 3A**) or toward the right atrial appendage to prevent sinus dysfunction. All valves and cardiac chambers are inspected for vegetation, clots, or foreign bodies. Some surgeons perform donor left appendage ligation at the back table to reduce the risk of the embolization. After finishing this step, the heart is brought to the surgical field for implantation.

3.3 Implantation

Donor heart is held outside the recipient chest cavity on the left side, the back of the heart is faced up. Then implantation starts with running double-armed 3-0 polypropylene suture.

First suture is very important for orientation and runs from the remnant left atrial cuff at the confluence of the left superior and inferior pulmonary veins and through the donor left atrial cuff near the base of donor left appendage. After passing the suture multiple times, the allograft is parachuted into the chest cavity and suturing is continued in a running fashion posteriorly and medially to the inferior aspect of the interatrial septum. Then the second arm is run along the roof of the left atrium till meet with the other end. Assessment of size discrepancy is very important in each suture between the donor and recipient, plication of access tissues might be necessary to achieve good hemostasis and anatomical geometry. Most centers use constant insufflation of carbon dioxide into the mediastinum to reduce the amount of intracardiac air. The right atrial anastomosis is performed in a running fashion similar to the left, with the initial anchor suture placed either at the most superior or inferior aspect of the interatrial septum so that the ends of the suture meet in the middle of the anterolateral wall (**Figure 3C**).

The end-to-end pulmonary artery anastomosis is performed using a 5-0 polypropylene suture beginning with the posterior wall from inside of the vessel and then completing the anterior wall from the outside. It is crucial that the pulmonary artery ends be trimmed to the appropriate length to eliminate any redundancy in the vessel that may cause kinking.

Finally, the aortic anastomosis is performed using 4-0 polypropylene sutures with a technique similar to that for the pulmonary artery, except that some redundancy is desirable in the aorta to facilitate visualization of the posterior suture line. It is important to get good hemostasis for this suture line as bleeding in the posterior wall of the aortic anastomosis is difficult to repair after the heart is reperfused. Toward this end, some surgeons performed a two-layer aortic anastomosis with or without bolstering with a strip of recipient's pericardium (**Figure 3D**).

Re-warming usually is begun at the start of the pulmonary arterial anastomosis. Routine deairing techniques are then employed and temporary pacing wires are placed in the right ventricle and atrium. Lidocaine (100–200 mg intravenously) and methylprednisone (10 mg/kg) is administered, and the aortic cross-clamp is removed. Cardioversion and temporary pacing are usually needed in most patients. A needle vent is inserted in the ascending aorta for final deairing, and infusion of inotropes is initiated, and suture lines are inspected carefully for hemostasis. The patient is weaned from cardiopulmonary bypass, heparin is reversed, and after hemodynamic stability, the cannulas are removed. Following insertion of mediastinal and pleural tubes, the sternotomy incision is closed in the standard fashion.

The advantage of the biatrial technique is its simplicity that allow the operation to be performed quickly and less time on cardiopulmonary bypass. However, when compared with the bicaval technique it has several drawbacks, including a large common (combined donor's and recipient's) right and left atrium, with distorted geometry that can lead to higher incidence of mitral and tricuspid valve incompetence, rhythm disturbances, and tendency of thrombus formation and septal aneurysm [31, 32]. Because of these drawbacks the biatrial technique has been mostly replaced by the bicaval technique.

4. Bi-caval technique of heart transplantation

Sievers and co-workers [33] in 1991, and the Wythenshawe group [16] in 1993, introduced into clinical practice the bi-caval transplantation technique (BC), characterized by two arterial, one left atrial, and two caval anastomoses. The recipient cardiectomy is performed similar as in the biatrial technique, except most of the wall of the right atrium is removed to create SVC and IVC stumps and a cuff of left atrium that contain orifices of all pulmonary veins.

The superiority of the BC technique has been shown in many publications; therefore it has been the preferred techniques in most transplant centers while the biatrial techniques are used only in selected cases [34–40].

4.1 Cardiectomy

Preparation for to place the recipient on cardiopulmonary bypass is as described in the biatrial technique. Native cardiectomy is started out as in the biatrial technique to remove the heart, leaving the left and right atrial cuffs (**Figure 3D**). The anterior and lateral walls of the right atrium are removed, and the SCV and IVC are completely

Bi-caval Heart Transplant Technique and its modification

Figure 4. Bicaval technique of heart transplant. (a) Standard bi-caval technique, which include complete excision of the right atrium and bicaval separation. (b) Modified bi-caval technique, include partial excision of the right atrium by keeping the posterior wall that connects the SVC and IVC.

disconnected from the right atrium in preparation for the end-to-end anastomosis to the corresponding donor cava (**Figure 4A**). Attention should be made to avoid damaging the recipient right pulmonary vein. In addition, the cutting edges of the right and left atria tend to bleed, therefore it is important to get good hemostasis with cautery, or suture ligatures because some areas will be inaccessible after implantation.

4.2 Donor heart preparation

The donor heart preparation for bicaval technique is similar to the one for biatrial technique with the exception that the donor right atrium is left intact; the SCV and IVC are not divided posteriorly, and their cut ends are left open (**Figure 4A**).

It is important to leave a generous the donor SCV remnant (usually at or above the azygous vein) to avoid tension on the SCV anastomosis. Therefore, during donor harvesting the SCV should be divided above the junction with the innominate vein.

4.3 Implantation

The most commonly used orthotopic heart transplant technique is today the bicaval technique (**Figure 4A**). As we described in the previous technique, donor heart is held outside the recipient chest cavity on the left side, the back of the heart is faced up. Then implantation starts with running double-armed 3-0 polypropylene suture. First suture is very important for orientation and runs from the remnant left atrial cuff at the confluence of the left superior and inferior pulmonary veins and through the donor left atrial cuff near the base of donor left appendage. After passing the suture multiple times, the allograft is parachuted into the chest cavity and suturing is continued in a running fashion posteriorly and medially to the inferior aspect of the interatrial septum. Then the second arm is run along the roof of the left atrium till meet with the other end. Assessment of size discrepancy is very important in each suture between

the donor and recipient, plication of access tissues might be necessary to achieve good hemostasis and anatomical geometry. Individual end-to-end anastomoses of the IVC performed following the left atrial anastomosis. The aortic, pulmonary arterial and IVC and SCV anastomoses can be done in a single aortic cross-clamp. As an alternative, to shorten donor ischemic time, the aortic anastomosis is performed immediately after the left atrial anastomosis and the aortic clamp is removed, allowing the donor heart to be reperfused while the remaining anastomoses are done with the heart beating.

In our practice, after we finish the left atrial anastomosis, we suture the posterior wall of the IVC anastomosis (the anterior wall after removal of the aortic cross clamp). Next, we perform the aortic end-to-end anastomosis with 4-0 polypropylene sutures. We use a strip of recipient's pericardium and incorporated it with the suture line, especially the back wall, to bolster it. Some surgeons use a double layer suturing technique to achieve hemostasis. After completion of the aortic anastomosis, we place temporary pacing wires into the right ventricle, remove the aortic cross clamp after de-airing, and start re-perfusing the heart to reduce the ischemic time.

Most often, the heart needs cardioversion and temporary pacing to keep in an organized rhythm.

Next, the pulmonary arterial anastomosis is performed, using 5-0 polypropylene sutures. We do not tie the sutures it at this stage but use it to remove air from the right ventricle after the caval tapes are removed. To keep the operating field dry, we place a flexible sump suction in the right atrium via the SVC and another in the recipient's pulmonary artery stump. The SVC and the anterior portion of the IVC anastomosis are then completed.

If the donor IVC opening is small, an inverted V cut could be made in the donor IVC opening to accommodate the remaining recipient tissues. At the completion of all anastomoses, the caval tapes are removed, de-airing of the RV is done, and the patient is weaned off cardiopulmonary bypass. After hemostasis is achieved, the sternum is closed in a normal fashion.

5. Modified bi-caval heart transplantation

Modified bi-caval technique was first introduced by Kitamura and Kakuta in Japan, by leaving the posterior atrial bridge of tissue between SCV and IVC intact. The advantages of this technique are: (a) to prevent retraction of the caval stumps that make the anastomosis difficult, (b) to keep the orientation of the caval stumps to prevent twisting of the anastomosis, and (c) to allow for adjusting the sites where the caval anastomoses are done in case of extreme donor-recipient size mismatch with the donor heart much smaller than the recipient's. With the presence of caval snares, the anatomical orientation can be lost, thus the anastomoses may be twisted or kinked. Furthermore, the caval end-to-end anastomosis in the original bicaval technique may become stenotic due to inadequate donor intercaval length in size-mismatched donor, causing excessive tension on the suture line. By leaving a thin strip of the posterior wall of the right atrium as a bridge connecting the superior and inferior venae cavae, it is easy to adjust the amount of atrial excision to the donor heart size. The modified bicaval anastomosis technique allows for an adjustable caval anastomosis to compensate for the size mismatch. The modified bicaval technique may result in lower incidence of late caval anastomotic stricture because the anastomosis can be performed with no tension or kinking. Its advantages have been elucidated in several studies [41–43].

5.1 Cardiectomy

Cardiectomy in modified bi-caval is very similar to the original bi-caval techniques. The only difference is not to completely transect the right atrium. Most of the lateral and anterior walls of the right atrium are resected, leaving the posterior wall intact to connect to the SVC and IVC (**Figure 4B**). The end-to-end caval anastomoses are performed by incorporating the posterior wall of the right atrium into the suture line. In some cases, it is easier to perform the IVC anastomosis if the recipient IVC is disconnected from the native right atrium (**Figure 4B**, dotted line).

This technique will facilitate the orientation of the bicaval anastomoses. In addition, the anastomoses will be easier to perform because there is no retraction of the SVC and IVC cuffs into the caval cannulae. Furthermore, with a V-shape cut in the donor SVC stump (**Figure 4A**), the SVC anastomosis is widened, with less chance of becoming stenotic.

5.2 Donor heart preparation

The donor heart preparation is similar to the bi-caval technique. The only difference is to make a longitudinal (about 3 cm) V shape incision in the posterior aspect of the donor SVC, using the azygos vein as a marker. This incision will help create a wide SVC anastomosis and help orienting the donor SVC (with the apex V corresponding to the posterior midline of the recipient SVC) to prevent twisting.

5.3 Implantation

Implantation of modified bi-caval is very much similar to the original bi-caval technique. However, care should be taken to ligate all opening of thebesian veins in the remnant of the right atrial wall to prevent bleeding.

In our experience, the posterior wall of the IVC anastomosis is better sutured from the assistant's side starting lateral to medial posteriorly and using the other arm the same way anteriorly. The SVC anastomosis starts from the most caudal part of the V shaped cut in the donor side to the middle part of the back wall of the RA with 4-0 polypropylene suture. It is better to tie down the first stitch, then run one arm anterior-lateral, and the other arm anterior-medial, then tie both in the front. As previous techniques, the SVC, IVC, and pulmonary anastomoses can be done after the cross-clamp is removed, which is our preferred technique. Hemostasis is achieved and CPB is weaned, chest is closed in a normal fashion as mentioned before.

6. Total heart transplantation

Yacoub, Banner, and Dreyfus [17, 44, 45] proposed a more anatomical surgical technique of bi-caval implantation, with complete excision of the recipient's right and left atria and direct anastomoses to the left pulmonary veins, right pulmonary veins, IVC and SVC. The rationale for this technique is to avoid non physiological geometry, which can lead to higher incidence of mitral and tricuspid valve incompetence, rhythm disturbances and tendency of thrombus formation and septal aneurysm [31].

6.1 Cardiectomy

Following median sternotomy, vertical pericardiotomy, and CPB establishment as explained previously. Cardiectomy is started in similar way as bicaval technique. The great vessels are transected above the semilunar valves, whereas the atria are incised along the atrioventricular grooves, leaving the right and left atrial cuffs behind. The lateral and anterior wall of the right atrium are removed, and the SVC and IVC are disconnected from the posterior remnant of the right atrium. The special feature of this technical is to separate the left pulmonary veins from the right veins, by excising the back wall of the left atrium to create two separate left atrial cuffs: one on the right that contains the right superior and inferior pulmonary veins, and one on the left with the left superior and inferior pulmonary veins.

6.2 Donor heart preparation

The donor heart preparation is similar as in bi-caval technique. However, harvesting of the donor heart is slightly modified to include the four pulmonary veins intra-pericardially. The tissue bridge between the superior and inferior pulmonary veins on each side is divided to create a single left and right orifices. At the end of preparation, the donor left atrium should have two oval openings on each side (**Figure 5**).

6.3 Implantation

This procedure is more technically difficult than the standard bi-caval orthotopic transplantation.

The total anastomosis in this technique is six, including two in left atria. The procedure starts by implanting the left recipient pulmonary vein button to the corresponding orifice on the donor left atrium. Next the right pulmonary vein button is

Figure 5.
Total heart transplant include; complete excision of the recipient's left and right atria, leaving separated SVC, IVC, and separate left atrial cuffs around left and right pulmonary veins.

anastomosed to the corresponding orifice on the donor left atrium. The suture line is started on the posterior aspect of both orifices. After finishing this step, the inferior vena cava anastomosis is completed and the rest of the procedure as described before for the bi-caval technique (**Figure 5**).

The disadvantage of this technique includes the marginally prolonged ischemic transplantation time, which is likely of no clinical relevance, as well as the potential for stenosis at the level of the venous anastomoses. Both problems, however, can be avoided with experience. Bleeding in the back wall of the left atrium is more difficult to control. The technique of total heart transplantation is more challenging but without convincing evidence of physiological or clinical advantages over the bicaval technique. Furthermore, with the advance of lung transplantation, a donor often donates a heart and both lungs, making preservation of an intact left atrium during organ retrieval difficult. Therefore, the technique of total heart transplantation has never been widely adopted.

7. Special considerations for heart transplantation in patients with end-stage congenital heart diseases

Techniques of heart transplant in patients with end-stage congenital heart diseases (CHD) is complicated and depends on the anatomical abnormalities. These techniques are beyond the scope of this chapter. However, will go through some special considerations.

CHD are diagnosed during infancy with 59% of the cases during the first year of life, 37% of children age 1–10 years, 23% of adolescent patients age 11–17 years, and 3% of adults [46, 47]. Heart transplant for CHD has some unique challenges, particularly those who have had previous repair or palliation. Over the years, indications for heart transplant in children and infants has changed as most of the CHD advanced recently. Fewer complex single ventricle anomalies required HT as a primary treatment. Many examples heart transplant is indicated for two-ventricle anomalies such as Ebstein's anomaly, tetralogy of Fallot, truncus arteriosus, and Shone's complex, and d-, 1-TGAs anomalies. However, failure of surgical palliative surgery is becoming the main indication for heart transplant in congenital heart diseases.

Visceral heterotaxia may add to surgical complexity but do not contraindicate HT. Patients with systemic complications of Fontan physiology represent a unique and expanding group being referred for HT. Absolute anatomic contraindications to HT in CHD are rare, but may include severe diffuse hypoplasia or pulmonary arteries or irreparable pulmonary venous malformations. The decision on when to recommend HT patients with CHD can be difficult, requiring serious consideration on the long-term risks and benefits. In general, the classic timing of listing for HT for any indication has been when the expected survival at 2 years is 50% [48, 49].

7.1 Consideration of donor heart

Oversizing is the main problem in the donor heart and should be avoided when is selected.

Specially in patient with fixed and scarred mediastinum. The ratio between donor-recipient should not be more than 2:1, with exception in recipients with elevated PAP.

Cardiac and vascular tissues recovered during procurement are very much dependent on recipient anatomy, anomalies, and prior intervention. In general, it is advised to obtain en bloc tissues with the heart such as innominate vein with the SVC, full length of the pulmonary artery including right and left pulmonary arteries branches. Most of the time it is preferred not to have a lung team during recovery and to share tissues.

As we mentioned before, communication between recovery team and transplanting team is very important to reduce the ischemic time, cardiopulmonary bypass time, and unnecessary delay. Communication and timing between both teams is very critical.

7.2 Consideration of operative techniques

As we mentioned HT in CHD usually performed after multiple palliative surgeries, and that could be very challenging due to adhesions and identifying anomalies and corrections previously performed. In addition, vascular access for lines placements can be challenging as well, and sometimes needs direct cutdowns. Topical cooling measures are initiated early, same with defibrillator pads. Extra cushion is taken when performing sternotomy to avoid massive bleeding and air embolization. Most of the time central cannulation is possible in pediatric heart transplantation. However, alternative access should be considered and prepared, such as groins and subclavian or axillaries. It is possible to simplify the CPB by placing a single venous cannula. In difficult cases, deep systematic cooling and circulatory arrest might be needed to finish the transplant. If the pericardial space is small, the left side of the pericardium is excised, and pleural cavity is opened to expand the cavity. Minimizing dissection in that area is desirable to avoid damaging the phrenic nerve. Multiple techniques have been described for complex cardiac malformation [50, 51]. In the case of abnormal situs and bilateral SVCs, atrial flaps and donor brachycephalic vein, cavo-caval connection could be performed. If the recipient had reconstruction of the brachiocephalic vein, the ascending aorta is kept long to perform retro-aortic vein placement or short to perform ante-aortic vein placement. Usually, the extra donor pulmonary artery tissues are used to correct the native pulmonary anomalies.

In some cases, anastomosis of the pulmonary artery laterally may be required with dextrocardia.

In patients with visceral heterodoxy or situs inversus, where the pulmonary atrium is midline or shifted to the right, the donor heart left pulmonary veins are oversewn, the left atrium is opened between the right pulmonary veins, and then anastomosed to the recipient's right-sided left atrium.

Multiple factors contribute to increased risk of bleeding after HT for CHD. These factors include chronic anticoagulation, liver dysfunction, dense adhesions, multiple thoracotomies, collateral vessels, splanchnic venous congestion, prolonged operative and CPB times, cyanosis, and thrombocytopenia.

8. Summary

The technique of heart transplantation has evolved over more than a century, from an experimental procedure to test the vascular anastomosis to the biatrial, bicaval and total heart transplantation techniques (**Figure 6**). The field has been built on the creativity and tenacity of many people of different disciplines to provide a therapeutic

Summary of Recipient Heart Preparation in different Techniques

Figure 6. Summary of recipient's preparation for different heart transplant techniques. Preparations for bi-atrial (a), bi-caval (b), modified bi-caval (c), and total heart transplant (d) techniques.

option that has improved and prolong the lives of many. The field needs similarly talented people and resources to overcome the next frontiers to make the organ last longer with transplantation tolerance, and to expand the donor pool, including donation after circulatory death, and xenografts.

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