

Congenitally Corrected Transposition of the Great Arteries

Nancy A. Ayres, Emad B. Mossad, Charles D. Fraser Jr.

Anatomical Considerations

Congenitally corrected transposition of the great arteries (ccTGA) is an uncommon congenital cardiac lesion characterized by atrioventricular and ventriculoarterial discordance (“discordant transposition”). While the most frequent segmental anatomic arrangement in ccTGA is usual atrial arrangement, left-handed ventricular topology, and posterior and leftward position of the aorta with respect to the PA (atrial situs solitus, L-looped ventricles, and L-malposed great vessels {S,L,L} according to the van Praagh classification), the condition may also present with complete mirror-image anatomy: mirror-image atrial arrangement, right-handed ventricular topology, and rightward location of the aorta with respect to the PA (atrial situs inversus, D-looped ventricles, and D-malposed great vessels {I,D,D}) (Figure 15-1).

The hallmark of ccTGA is the association of the *morphologic* RV with the systemic circulation. While the coronary anatomy is “mirror-image” in most patients, the coronary origins and branching may be highly variable. In ccTGA, the morphologic tricuspid valve (TV or systemic atrioventricular valve) is often apically displaced with septal attachments leading to it often being referred to as “Ebsteinoid”. In fact, this is an incorrect designation in that the apical displacement is not associated with an atrialized portion of the morphologic RV.

The cardiac conduction system is abnormal in ccTGA. The AV node is displaced in an anterior and superior location in most patients, and the bundle of His is elongated. There may be two AV nodes and the incidence of an accessory atrioventricular pathway (as in Wolff-Parkinson-White syndrome) is significant.

Pathophysiology and Clinical Presentation

Clinical presentation of ccTGA is highly variable and relates to anatomic substrate and ventricular function. This leads to a complex set of diagnostic and management considerations. Historically, many individuals with ccTGA with intact ventricular septum (IVS) lived well into adult life undetected, presenting later in life with left AV valve (tricuspid) regurgitation, depressed systemic RV function, or spontaneous AV block (frequent in this condition). In current practice, many patients are now presenting for management consideration in the absence of overt symptoms. This is often the case in patients picked up on screening fetal echocardiography or some other form of prophylactic postnatal assessment (murmur evaluation, serendipitous CXR revealing abnormal cardiac silhouette, screening ECG).

Symptomatic presentation typically relates to the presence of associated cardiac defects, which occur in more than 85% of patients, or ventricular dysfunction. The most common associated cardiac defects are a perimembranous VSD (70%), pulmonary stenosis (PS) or LVOT obstruction (LVOTO, 56%), or AV conduction abnormalities (5%). The left AV valve (tricuspid) is abnormal in more than half the patients, with apical displacement being common.

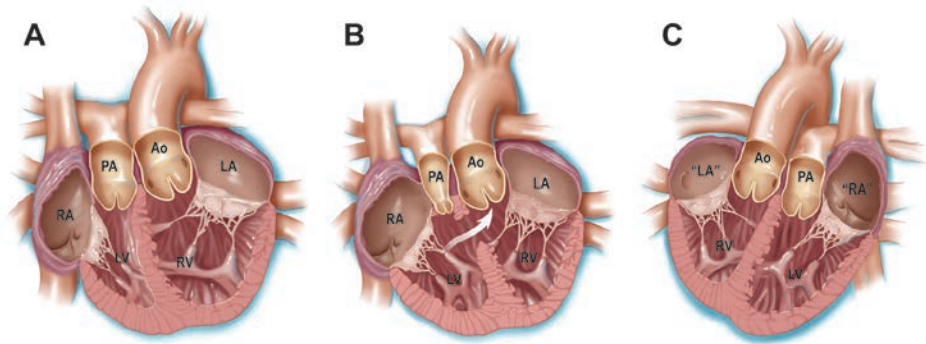


Figure 15-1. Morphological variants in ccTGA. A) Usual arrangement in ccTGA with IVS (levocardia). The morphologic RA is connected to the morphologic LV, which is connected to the PA, and the morphologic LA is connected to the morphologic RV, which is connected to the aorta. B) ccTGA with VSD and LVOTO (PS). The arrow indicates the direction that the baffle would need to take if connecting the LV to the aorta. C) ccTGA with mirror-image anatomy and dextrocardia. The morphologic RA is on the left and the morphologic LA is on the right (atrial situs inversus). Ao: Aorta.

Symptomatic Presentation

Patients with ccTGA and a large VSD may present early in life with signs/symptoms of CHF. The VSD may be nonrestrictive or pressure-restrictive. The latter concern is of importance in determining the conditioning of the morphologic LV (to be discussed below).

A common association of lesions in ccTGA includes VSD with some degree of LVOTO or even true pulmonary atresia. In the absence of other sources of pulmonary blood flow, the degree of LVOTO correlates with systemic arterial desaturation/cyanosis. In patients (newborns) with true pulmonary atresia, pulmonary blood flow is dependent on ductal patency.

Systemic (tricuspid) AV valve regurgitation (TR) may be found in association with the other cardiac lesions or as an “isolated” phenomenon in patients with ccTGA with intact septum. Significant TR leads to symptoms of CHF and is an important clinical marker of concern (see below).

Systemic RV dysfunction may present early or late in life. Progressive reduction in RV ejection fraction (RVEF) in the setting of a small VSD or intact ventricular septum (IVS) leads to RV dilation and secondary tricuspid annular dilation, which will exacerbate TR. Many believe that absent a morphologic problem with the TV, TR becomes an early indicator of RV dysfunction.

Asymptomatic Presentation

Given the widespread use of screening prenatal ultrasound (and subsequent fetal echocardiography when an anatomic issue is identified), there are increasing numbers of children presenting early in life for consideration of intervention for ccTGA. In asymptomatic individuals, this becomes a very complicated management scenario,

particularly in the setting of “normal” RV function, IVS or small pressure-restrictive VSD, or trivial TR.

Some individuals present with minimal or no symptoms despite apparently significant hemodynamic lesions. Patients in this category may have significant reduction in RV function with or without significant TR before overt symptoms appear.

Diagnosis

- **CXR.** May show levocardia, mesocardia, or dextrocardia. In the setting of depressed RV function and/or significant TR, there may be cardiomegaly and congested lung fields. Patients with significant LVOTO (PS) may exhibit oligemic lung fields.
- **ECG.** There may be an abnormal P-wave and increased P-R interval. Early repolarization (delta waves) may indicate an accessory AV conduction pathway. Third-degree AV block may occur spontaneously or as a complication of catheter or surgical intervention.
- **Echocardiography.** Mainstay of clinical diagnosis. Important elements of a thorough echocardiographic examination include:
 - Status of the interatrial septum.
 - Systemic and pulmonary venous connections.
 - Status of the interventricular septum. Presence, size, and location of VSDs. Estimated pressure gradient between ventricles.
 - AV valve anatomy and function. In the setting of significant TR, careful delineation of morphologic substrate is critical to decision making (displaced leaflets, annular dilation, dysmorphic leaflets, prolapse, chordal rupture). Morphologic MR is also possible and there are rare cases of a mitral cleft in ccTGA. The status of the mitral valve and need for repair become critical in the consideration of a “double switch” (see below).
 - Ventricular function. Estimated ejection fraction (shortening fraction) of both ventricles. Location/geometry of the interventricular septum provides inferential evidence of RV/LV pressure ratio (see also “double switch”). Status (thickness) of the LV free wall may be useful in situations of LV conditioning (“retraining”).
 - Right and left ventricular outflow tract assessment. LVOTO in the setting of a large VSD is frequent. Organic RVOT obstruction (RVOTO) may be associated with aortic arch hypoplasia/coarctation.
 - Semilunar valve morphology and function. Critical in the consideration of anatomic or physiologic repair.
 - Aortic arch anatomy and evaluation for obstruction/coarctation.
- **Cardiac catheterization.** *Diagnostic* catheterization may be an important adjunct to clinical decision making in association with other diagnostic modalities. In the setting of multiple muscular VSDs, cath may be very useful in discerning anatomic detail (and also offers the option of interventional device closure where appropriate). Typically, echo Doppler estimates of pressure gradients are adequate for decision making in most scenarios, but any uncertainty should be carefully assessed by hemodynamic cath. Assessing PVR is critically important in settings where there is suspected elevation. This latter scenario is particularly important if a Fontan

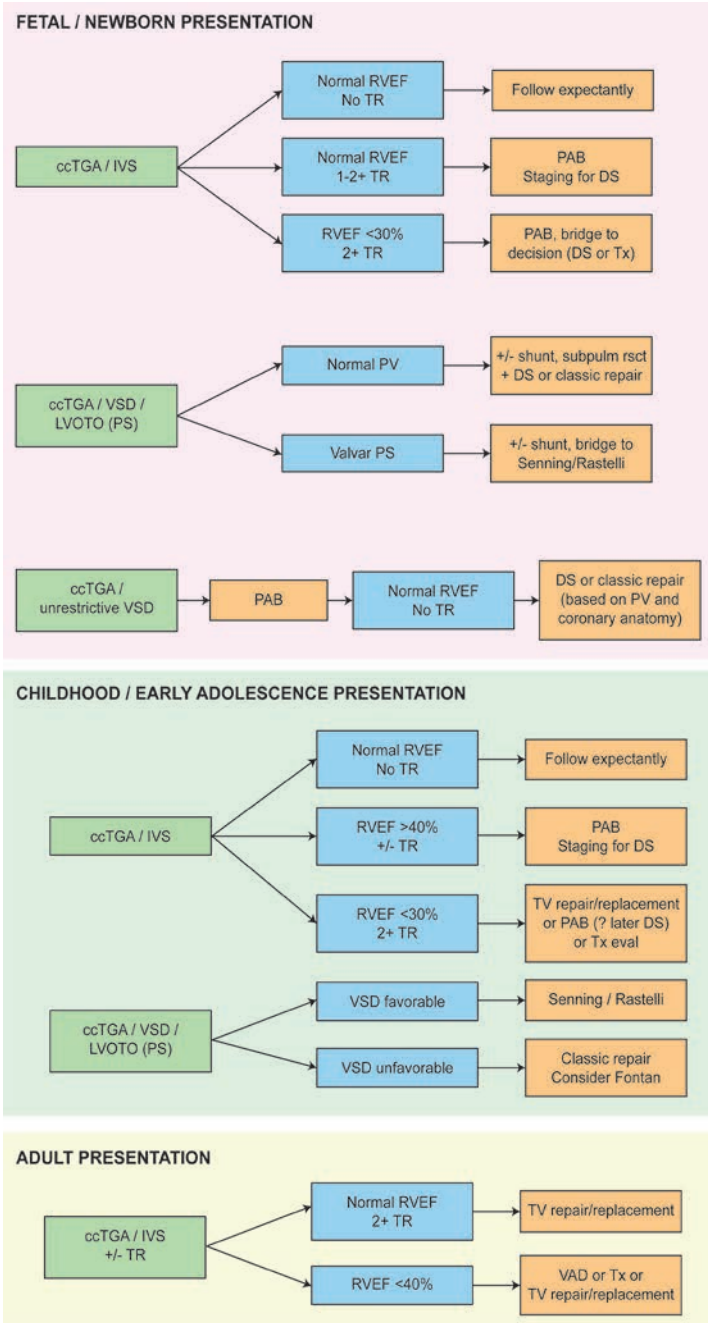


Figure 15-2. Management algorithm of patients with ccTGA depending on anatomy and age at presentation. DS: double-switch operation, PV: pulmonary valve, RVEF: RV ejection fraction, Tx: transplant.

palliation is being considered or in cases of late presentation of a patient with a large VSD and unprotected pulmonary vasculature. Diagnostic cardiac catheterization is also a useful adjunct when assessing preparation of a formerly deconditioned morphologic LV in the setting of preparation (PA banding) for a “double switch” or anatomic repair (see below). *Therapeutic* cardiac catheterization may be helpful in settings where there are difficult to reach, apical muscular VSDs that are amenable to catheter-delivered device closure. In the setting of patients who have undergone an atrial switch operation, remedial cardiac catheterization and intervention may be useful and necessary in the settings of baffle limb obstruction or leakage.

- **Cardiac MRI.** The utility of MRI for the majority of patients with ccTGA is debatable; most questions can be answered with echocardiography. An interesting scenario that has gained increasing popularity is the assessment of LV wall thickness over time in patients who are undergoing LV preparation for a double switch. Investigators have also used MR viability studies as an adjunct to this decision tree.

Surgical Considerations

There is ongoing debate among surgeons and centers concerning the optimum surgical strategy for various forms of ccTGA. Categorical options include a “classic” repair in which the morphologic RV is maintained as the sole systemic ventricle, the “double switch” where the morphologic LV is aligned with the systemic circulation, and single-ventricle palliation. To date, there are no definitive data to clarify the issue of which operation offers the patient not only the best short-term outcome, but also the greatest opportunity for a durable long-term solution. However, it is clear that when the RV is aligned with the systemic circulation, the presence of significant TR portends ultimate RV failure and as such, mandates careful attention and justifies surgical intervention. Figure 15-2 provides an overall guide of the management approach at TCH.

Classic Repair

The term “classic” repair has been typically associated with a biventricular reconstruction in which the morphologic RV is relegated to remain the *systemic ventricle*. This arrangement may place the patient at risk of early or late systemic RV failure and/or progressive morphologic TR. As such, assigning the morphologic RV to the systemic circulation has important, often irreversible consequences. There are certain settings in which choosing a classic repair may be the wisest option:

- In certain patients with ccTGA/VSD/LVOTO (PS or pulmonary atresia) with an *inlet VSD* or remote *muscular VSD*, constructing an unobstructed pathway from the morphologic LV to the aorta (Senning-Rastelli) may be problematic. We have believed that in such settings, if the morphologic RV and tricuspid valve have good function (minimal or no TR, and no significant apical displacement), a classic repair may represent a better alternative.
- In cases of ccTGA with IVS, the morphologic LV may not be capable of supporting the systemic circulation if it has not been working at systemic pressure (involved LV). In this context, if the LV has not responded to reconditioning (PA banding), it is imprudent to proceed with a “double switch”.

- Patients with an abnormal pulmonary (neoaortic) valve that would be suboptimal as the systemic semilunar valve.
- An additional and very important consideration is whether or not the family is willing to take on the significant perioperative and ongoing risk of choosing the double switch. It has been well-documented that in large series, the ability to predict the ability of the morphologic LV to durably sustain the systemic circulation after a double switch, particularly if the LV had to undergo a period of reconditioning, is imperfect. The sobering series from Birmingham, England (Winlaw et al. 2005) indicated that after a period of LV retraining and subsequent double switch, the probability of freedom from death or transplant at approximately 10 years of follow-up is in the range of ~75%. Therefore, in counseling families, the team is justified and more specifically responsible for being circumspect about the option of a double switch.

In closing the VSD as part of a classic repair, the surgeon must be knowledgeable about the anterior AV node and His bundle. In the typical outlet/perimembranous-type VSDs, sutures should be carefully placed on the RV side of the septum to avoid surgical AV block. If an LV-to-PA conduit is necessary, care must be exercised to avoid major epicardial coronary arteries and undermining or avulsing important papillary muscle support for the morphologic mitral valve.

The Double Switch

The term “double switch” has been loosely applied to 2 very different physiologic and anatomic situations. The most straightforward situation is in the setting of ccTGA, outlet/perimembranous VSD, PS or pulmonary atresia. In these situations (including patients with situs inversus), a Senning-Rastelli operation can be accomplished to commit the morphologic LV to the systemic circulation. The basic principles include a strategically placed right ventriculotomy, construction of an LV-to-aortic tunnel (we favor autologous pericardium), a Senning atrial switch (Figure 15-3), and placement of a valved conduit from the RV to the PAs. A variation of this proposition that has been promoted by Hanley at Stanford University (Malhotra et al. 2011) is to perform a bidirectional Glenn shunt and a “Hemi-Mustard Rastelli” (Figure 15-4). In either event, results with this operation have proven to be very predictable and durable.

The more challenging situation occurs in the setting of either ccTGA/IVS or ccTGA/VSD in which the goal is aligning the morphologic LV with the systemic circulation. This is achieved by performing an arterial switch operation (ASO), Senning atrial switch, and VSD closure, if applicable. Each scenario is briefly described below.

ccTGA with “Prepared” Morphologic LV

If the morphologic LV has never had the opportunity to involute, it is arguably well prepared to support the systemic circulation. Scenarios include ccTGA with non-restrictive VSD where the morphologic LV has always worked at systemic pressure and the more controversial setting of *newborns* with ccTGA/IVS. In the former situation, the surgeon needs to close the VSD, noting the displaced AV node and His bundle as per above, followed by ASO and Senning operation. The procedure is complex and the heart is arrested for extended periods of time. As such, we have often chosen intermittent

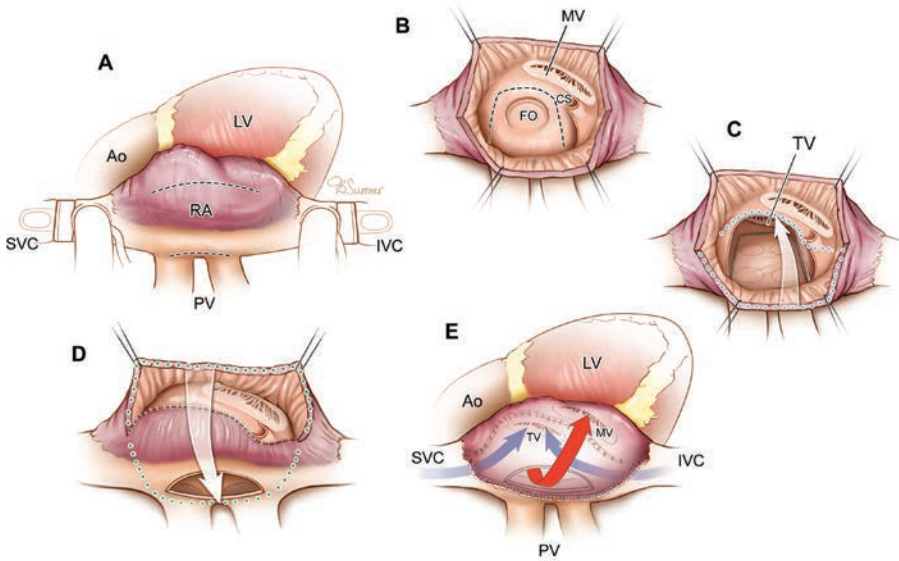


Figure 15-3. Senning atrial switch. Using a series of autogenous flaps, the pulmonary venous flow is directed to the anteriorly located LV, while the SVC and IVC flows are directed into the posteriorly located RV. Incisions are made in the RA and the LA just anterior the pulmonary veins (A), a flap of atrial septum is created (dashed line in B) and sutured posteriorly around the pulmonary veins (C). The posterior free wall flap of the RA is sutured around the atrial septal defect (dotted line in C), therefore redirecting the flow from the SVC and IVC down towards the posteriorly located TV. The anterior free wall flap of the RA is sutured around the incision made anterior to the pulmonary veins (D) to redirect the flow from the pulmonary veins to the anteriorly located mitral valve. Panel E shows the resulting flow redirection. Ao: aorta, CS: coronary sinus, FO: foramen ovale, MV: mitral valve PV: pulmonary veins.

periods of aortic cross-clamp interspersed with periods of myocardial reperfusion to optimally provide predictable myocardial protection.

In the setting of ccTGA/IVS, the morphologic LV (subpulmonary ventricle) will start to involute soon after birth when the PVR and PA pressure naturally drop. This scenario is very analogous to the setting of simple or D-transposition of the great arteries (D-TGA) with IVS. As such, some surgeons have advocated for a very aggressive newborn approach for ccTGA/IVS by performing an ASO and Senning operation to align the LV with the systemic circulation before it has the opportunity to become deconditioned. We believe this aggressive strategy is unfounded. Although there are scattered published reports with favorable outcomes using the neonatal double switch, this approach has not been widely adopted and is currently not recommended for newborns at TCH.

ccTGA with “Unprepared” Morphologic LV

This is arguably the most challenging and controversial situation in the management of patients with ccTGA. Patients with ccTGA/IVS or pressure-restrictive VSD beyond

the newborn period will have an LV that is incapable of performing adequately at systemic workload if a double switch is performed. For this reason, the idea of “retraining” or reconditioning the morphologic LV by placing a PA band (PAB) has been applied to patients with ccTGA who may benefit from a double switch. As a basic concept, we believe that embarking on the challenging proposition of retraining the LV through PAB (often serial banding) followed by the ultimate double switch must be justified through objective evidence that the morphologic RV is incapable of remaining a durable systemic ventricle. Objective evidence of RV compromise includes RV ejection fraction decline, TR greater than mild (or progressing over time), a grossly displaced TV, or other evidence of impending RV dysfunction.

LV retraining is a very controversial subject and there is considerable inter-practitioner/interinstitutional debate about the optimal strategy. The prospect of retraining the LV is rather unpredictable and the long-term results of reconditioned LV performance after the double switch are inconsistent. As such, we have adopted a moderately conservative approach that includes careful and thorough consultation with the parents during which the various scenarios and potential risks are thoroughly discussed. If the parents agree to the recommendation of PAB retraining of the LV, the patient undergoes diagnostic testing to include TTE, MRI (to assess LV mass, LV wall thickness, and ejection fraction), and cardiac catheterization (to assess LV hemodynamics including peak LV systolic pressure and LV end-diastolic pressure). Of note, a coronary angiography is not required as ASO is able to be performed for all coronary artery branching patterns and ostial relationships.

Following diagnostic testing, the patient is taken to surgery for the initial PAB procedure. Under adequate general anesthesia and mechanical ventilation, and without inotropic support, the pericardium is opened (we usually just open the superior pericardium to facilitate subsequent sternal reentry) and a flexible pressure monitoring catheter is introduced retrograde from the main PA, through the pulmonary valve, and into the LV chamber. In the setting of ccTGA/IVS, it is typical to find a peak LV systolic pressure of

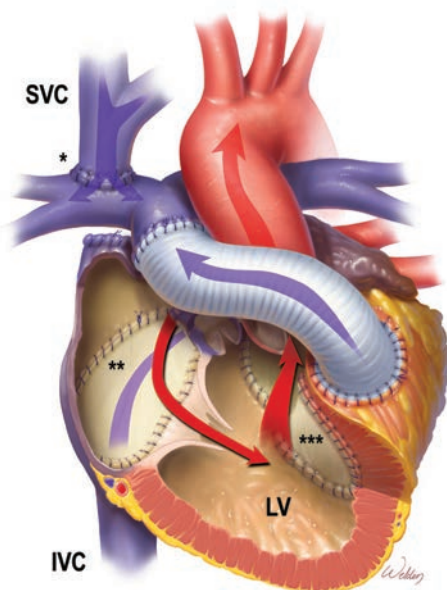


Figure 15-4. Hemi-Mustard/Rastelli operation. A bidirectional Glenn is created by connecting the SVC to the right PA (*), a “hemi-Mustard” baffle is created to redirect the flow from the IVC to the LA (**), and a baffle is created to redirect the flow from the right-sided LV to the aorta (***). A conduit is then placed to connect the left-sided RV to the PA. The pulmonary valve, if previously patent, is sewn shut.

well less than 1/3 systemic at the outset. A Dacron® tape is passed around the main PA (must be kept above the sinotubular junction to avoid impingement on and distortion of the pulmonary valve). The PAB is sequentially tightened while the surgeon, anesthesiologist, and echocardiographer carefully observe LV function, systemic hemodynamics, and LV systolic pressure. Our experience

TCH ccTGA experience (1995-2016) (De Leon et al. 2017)

Number of patients: 97

Median age at presentation: 2 months (0 days – 69 years)

Median follow-up: 10 years

10-year transplant-free survival:

- Classic (or no) repair (systemic RV) (n=45): 93%
- Anatomic repair (systemic LV) (n=26): 86%
- Fontan operation (n=9): 100%
- Ongoing palliation (PAB, shunt) (n=17): 79%

is that at the primary banding, it is typical that the LV cannot withstand or produce an LV systolic pressure >50-60% systemic in most cases. It is common to see the LV start to fail (dilation, low systemic BP) with bands that are tightened beyond this level. Once the PAB has been adjusted to its final tightness, it is prudent for the team to carefully observe the patient in the OR with the chest open for at least 30 minutes. We have seen situations in which an initial PAB tightness appears to be well tolerated only to find that the LV function starts to decline after some period of time.

The next level of controversy relates to the basic questions of how tight a band is tight enough (level of peak LV systolic pressure) and how long to retrain the LV. There is significant variability among institutions concerning answers to both of these questions. Given the uncertainty of the currently available methods to assess adequacy of LV retraining (LV systolic pressure, ejection fraction, LV wall thickness), we have favored a conservative approach. Our goal has been to achieve an LV systolic pressure of at least 80% systemic for a minimum of 6 to 12 months. At this point, if the LV appears to be managing the workload, we will offer the double switch.

The technical issues related to the double switch in ccTGA are somewhat different than the ASO for D-TGA. Typically, the aorta is anterior and leftward in ccTGA and it is not unusual for the great vessels to be almost side-by-side. This may make the coronary translocation more challenging. Furthermore, after a period of banding, the pulmonary sinuses of Valsalva may become very dilated. In this circumstance, it may be prudent to excise as much of the PA sinus as possible while translocating the coronary buttons. The surgeon should mobilize the coronary ostia as very liberal buttons of aortic wall and must be prepared to deal with all variations of coronary ostial origin and branching. Given the relationship of the great vessels, reconstructing continuity between the neopulmonary root and branch PAs may require an anastomosis that is extended out onto the left PA. The details of the atrial switch operation are also beyond the scope of this brief chapter. Given the fact that many surgeons have little experience with the Senning operation, several units have preferred to create a bidirectional Glenn shunt and “hemi-Mustard” connection under the premise that this may be more readily constructed with less potential for baffle limb obstruction.

The Fontan Operation

Given the various technical and management challenges we have outlined in preceding sections, many surgeons have argued that a Fontan operation may offer a much more straightforward management strategy, particularly for patients with cyanotic variants and in the setting of cardiac malposition (mesocardia or dextrocardia). There is no doubt that the Fontan operation is less technically demanding and in the current era, *acute operative risk is very low*. Whether a Fontan circulation represents a more favorable long-term strategy, however, is debatable. Exposing the liver and abdominal viscera to the obligate increases in systemic venous pressure initiates a relentless cascade of secondary consequences, the timing of which and the degree of derangement, are highly variable among individuals. Nonetheless, given the scope of the complexity of management options in ccTGA, a Fontan operation remains a viable option for selected individuals.

Suggested Readings

DeLeon LE, Mery CM, Verm RA, et al. Mid-term outcomes in patients with congenitally corrected transposition of the great arteries: a single center experience. *J Am Coll Surg* 2017;224:707-715.

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