What surgical improvements are needed to prove that anatomic repair is superior to physiologic repair in the majority of patients with corrected transposition of the great arteries?

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Alomair and colleagues deserve our admiration and respect for their very careful longer-term follow-up of a large cohort of patients with corrected transposition of the great arteries (ccTGA) undergoing physiologic or anatomic repair and their effort to address the oft-debated issue of which approach provides superior long-term outcomes. The cohort included 165 patients amenable to biventricular management spanning the interval from 1982 to 2015. Somewhat less-than-hoped-for results with a conversion to anatomic repair in the 1990s led to a transition back to physiologic repair, again with imperfect results. This led to selective use of anatomic repair in the early 2000s, followed by nearly uniform conversion to anatomic repair after 2005. To offer a more comprehensive comparison of all possible management strategies, their analysis included 38 patients with no need for intracardiac repair (although 4 patients underwent atrioventricular [AV] valve replacement), and 35 patients with {S,L,L} topology who underwent Fontan palliation. The authors provide a very thoughtful and tempered discussion of their data. They concluded that compared with physiologic repair, anatomic repair did not appear to provide an advantage with respect to survival or systemic ventricular function, and that AV valve function deteriorated in all groups except those with Fontan palliation. Based on a 90% 25-year survival in patients without surgery, they cautioned that “prophylactic” anatomic repair might not be justified.

We agree with many of the concerns expressed by Alomair and colleagues in their excellent review; however, we believe that caution must be observed when drawing conclusions as to the primary clinical approach when interpreting the data that the authors have provided, for 2 reasons. First, scrutiny of the provided survival curves demonstrates significant early attrition, as has been

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Central Message

It is our obligation to refine our surgical approaches to demonstrate the superiority of using the morphologic left ventricle as the systemic pumping chamber in ccTGA.

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recognized and reported by others.^{1,2} It is very likely that this reflects both patient selection as well as a longer-than-average learning curve for a complex operation. Today, at advanced centers, this component of the survival curve may be absent, shifting the optimal treatment approach. Second, the median follow-up for the anatomic repair group was 3.4 years, with 15 patients at risk 5 years after surgery. Longer-term follow-up is needed to make a definitive decision as to the best clinical approach. Given these issues, it might not be correct to posit nonsuperiority of anatomic repair in the current era. We trust most would agree that it would be more desirable to place the morphologic left ventricle (mLV) and the mitral valve (MV) in the systemic circulation, and that doing so earlier, before the onset of symptoms, likely would be beneficial. Finally, at 15 years, only 9 Fontan recipients were at risk. Although ventricular function and AV valve function were very good, is this adequate justification to consider this approach for a patient with 2 well-formed ventricles? Perhaps, but longer-term data are needed to justify that approach, given what is currently known about the other longer-term detrimental physiological effects of the Fontan circulation.

By definition, the anatomic correction using the mLV as the systemic pumping chamber and the MV as the systemic AV valve represents a group of procedures in which the AV discordance is “corrected” by an atrial switch (Senning or

Mustard), and ventriculoarterial discordance is “corrected” by an arterial switch operation (ASO), the Rastelli procedure, or translocation of the aortic root (Nikaidoh operation). Each of these procedures carries potential complications, affecting final outcomes. The question that we hope to address in this commentary is what surgical improvements are needed to prove that anatomic repair is superior to physiologic repair in the majority of patients with ccTGA.

CONSIDERATIONS RELATED TO THE ASO

Modified Senning Operation

The Senning procedure for ccTGA is technically more challenging because of the misalignment of the interventricular and interatrial septum and the reduced size of the right atrial free wall, which is associated with the high incidence of mesocardia or dextrocardia in {S,L,L} or levocardia or mesocardia in {I,D,D}. Especially in these scenarios, the modified Senning procedure might be very useful. Modifications to the original technique³ include the following:

1. Preservation of the superior vena cava–right atrium (SVC-RA) pericardial reflection to avoid damaging the sinus node
2. Cryoablation of the cavo-mitral isthmus
3. Complete resection of the interatrial septum, with effective cutoff of the superior aspect of the limbus of the fossa ovalis to avoid baffle obstruction from the SVC to the tricuspid valve (TV). At the same time, the trapezoid-shaped patch used for the posterior wall of the systemic baffle should be seated low beneath the SVC-RA junction.
4. Unroofing and incorporation of the coronary sinus venous system pathway
5. Creation of the pulmonary venous atrium using autologous pericardium in situ.

Today, with the technical aspect of the modified Senning procedure well established, the incidence of tunnel obstructions is <5% at major centers.³ Furthermore, the modified technique has the potential to provide adequate capacity of the pulmonary venous atrium, preserve optimal geometry of the MV, minimize damage to the sinus node, and make the coronary sinus accessible for electrophysiologic studies or intervention. Preventive ablation of the cavo-mitral isthmus might decrease the incidence of atrial reentrant tachycardia.⁴ The modified Senning procedure is highly reproducible and applicable, regardless of the situs and position of the apex of the heart.⁵

CONSIDERATIONS RELATED TO mLV TRAINING AND THE ASO

There is appropriate concern over the incidence of late mLV dysfunction, which has been reported to occur in 15% to 20% of patients at 20 years after anatomic repair.² The risk is increased in patients needing mLV training,

although other factors, such as late neoaortic regurgitation, post-anatomic repair MV regurgitation, heart block, and preoperative heart failure may play roles as well.^{2,6,7} We feel that in patients requiring mLV training, a novel form of pulmonary artery banding (PAB) may decrease strain on the mLV, potentially improving long-term function.

As a general rule, PAB is required in patients with intact ventricular septum beyond the third month of age, to enable training of the mLV to cope with the burden of the systemic circulation in preparation for a double-switch (DS) operation.⁸ The basic target is to achieve 75% of the systemic pressure in the mLV. However, excessive PAB tightening leads to reduced mLV function and myocardial edema. In some cases, optimal retraining of the mLV can be achieved only via sequential PAB.⁹ Age at the initiation of training is a critical variable. The Boston group has reported a greater risk of late mLV dysfunction in patients who were initially banded at age >2 years, whereas there was no incidence of late dysfunction in patients banded at age <2 years.¹⁰ The Paris group advocated early “prophylactic” PAB in asymptomatic ccTGA infants, which might protect the mLV from late failure in these patients.¹¹

The problem is that the relationship is by no means consistent.^{2,6,7,12} In general, the results in prepubescent patients are very good, but the response of older patients is less predictable and is associated with higher early and late mortality. The cutoff for retraining the mLV is around age 12 to 15 years.¹²

Enhanced mLV Training

The Sankt Augustin group⁸ proposed a more physiologic concept for mLV training, increasing not only the afterload, but also the preload, by placing “loose” PAB, achieving 50% to 60% of systemic pressure in the mLV, and unloading the mRV and increasing the mLV preload by creating an artificial atrial septal defect (aASD). This approach seemed to simplify postoperative management and provide gradual training of the mLV. In patients with a significant shunt at the atrial level ($Q_p/Q_s > 1.5$ and a defect size of at least 10 mm), it is known that the additional volume load will create a functional gradient across the pulmonary valve as the narrowest point in the pulmonary circulation.¹³ As long as the diastolic function of the mLV is preserved, the atrial shunt increases the transpulmonary gradient during physical activity, which in effect creates a form of intermittently elevated mLV strain.¹⁴ This has the theoretical advantage of avoiding continuous ventricular wall stress, potentially allowing longer periods of myocardial regeneration. In addition, a newly created aASD serves as a “pop-off” valve when afterload suddenly increases and the mLV is exposed to excessive (and potentially damaging) strain. An increased preload seems to promote the growth of the mLV, dynamically modulating the gradient across the PAB, providing intermittent training alternating with

periods of relaxation to optimize myocardial regeneration. Systemic pressure in the mLV can be achieved within 1 year of mLV training without re-PAB in younger patients, and successful DS can be performed without major perioperative complications. One potential disadvantage of this approach might be a temporary cyanosis owing to a right-to-left shunt at the atrial level and a risk of paradoxical embolization, but this was not observed in the series reported by the Sankt Augustin group.⁸

HEART BLOCK AND PACING

mLV dysfunction has been associated with a high incidence of the need for pacing and of prolonged QRS interval.⁶ Patients with ccTGA are at risk for complete heart block, even without surgery, and it has been estimated to affect approximately 2% of patients per year after diagnosis. Surgically acquired heart block is often related to resection of a left ventricular outflow tract obstruction (LVOTO) or to closure and/or enlargement of a ventricular septal defect (VSD). The incidence of surgically acquired heart block is up to 20%, with freedom from pacemaker implantation of 70% to 80% at 15 years.⁷ VSD closure should be performed with sutures placed on the mRV side of the septum; however, traction on the crux of the heart, particularly in {S,L,L} when the heart is in a mesocardiac or dextrocardiac position, may create a permanent heart block even if the sutures are carefully placed.³ In this specific anatomy, one should consider closing the VSD, working through the right ventriculotomy or the aorta, thereby eliminating undue tension on the crux cordis.

In the event that heart block occurs, biventricular pacing should be considered, given the several reports of progressive mLV dysfunction in patients with mRV pacing alone.¹⁵

CONSIDERATIONS RELATED TO THE RASTELLI PROCEDURE

Anatomic correction of ccTGA with VSD and LVOTO can be performed with minimal mortality and acceptable morbidity. Freedom from mLV dysfunction or heart transplant is 0 to 15% at a 10-year follow-up.^{2,3,16} The treatment option should be individualized based on the morphology of the LVOTO and the size and position of the VSD and the AV valves. The negative impact of complete heart block and intraventricular tunnel (IVT) obstruction on the long-term function of the mLV are well documented.^{2,6} To minimize the recognized morbidity associated with the different procedures, one might consider guiding the direction of the enlargement of the restrictive VSD, based on the anticipated position of the AV node with respect to the degree of misalignment between the interventricular septum and atrial septum. In situs solitus, an anterior position of the conduction system is expected, and the VSD is enlarged toward the apex. With minimal misalignment between the interventricular

and atrial septa seen in severe LVOTO, a posterior position of the AV node is a possibility, as are dual AV nodes that connect to a sling of conduction tissue.¹⁷ How the mesocardia or dextrocardia effects misalignment and the anatomy of the conduction system is unclear. An electrophysiological study might be helpful in planning the enlargement of the VSD. In situs inversus, anterior enlargement of the VSD might be performed. In specific cases with a patent LVOT, a Damus–Kaye–Stencel (DKS) anastomosis should be considered to minimize the risk of acquired heart block while providing 2 systemic outflows.¹⁸

CONSIDERATIONS RELATED TO THE AORTIC TRANSLOCATION PROCEDURE

Aortic translocation in ccTGA with a complex LVOTO is a challenging procedure that should be considered only if the anatomy is inadequate for an IVT as part of a Rastelli operation.^{19–21} The specific issue is the risk of damaging the conduction system during division of the outlet septum. In situs solitus, partial division of the muscular outlet septum does not result in complete heart block; however, care should be taken when suturing the patch around the septal defect to avoid injuring the conduction tissue.²² The position of the conduction system in situs inversus allows risk-free complete transection of the outlet septum.²²

SUMMARY

Results from the traditional approach of preserving the mRV as a systemic ventricle have clearly demonstrated that TV and mRV function is the Achilles heel of ccTGA physiology.^{1,23} In patients suitable for anatomic correction, universal improvement in the function of the RV and TV occurs when they are exposed to the lower pressures in the pulmonary circulation. Even in the presence of dysplasia of the TV, with severe preoperative regurgitation, concomitant TV repair is rarely needed at the time of the anatomic correction.^{2,3} On the other hand, in patients not suitable for anatomic correction, the native well-balanced pulmonary stenosis has a protective effect on TV and mRV function,²⁴ and thus preventive PAB with limited atrial septal communication might be useful as a long term or definitive palliation to mimic the favorable history of patients with ccTGA and limited LVOTO.

The long-term survival and functional benefits after anatomic correction have been well demonstrated in the group of patients with preoperative TV regurgitation.^{1,23} Whether the proposed refinements of our current practice will make a difference in the other patient groups remains to be seen. Clearly, we do not completely understand the limits of mLV training, particularly in older patients. In addition, the most appropriate methods for mLV training are not yet defined. Unless our methods improve, some patients will continue to present with severe heart failure,

and no meaningful surgical options other than mechanical circulatory support and cardiac transplantation. Perhaps regenerative technology, such as stem cell technology or other targeted medical therapies, will help improve mLV function in the future. Surgeons must be more familiar with the variability of conduction systems owing to different positions of the heart and misalignment of the interventricular and interatrial septa to properly execute VSD closure, creation of complex IVT, or performance of the Nikaidoh operation to minimize the incidence of surgical heart block. Careful patient selection is needed, with some patients better served by other surgical options. Finally, we believe that these complex unique surgeries should be performed in centers with appropriate experience with this lesion and a favorable postoperative environment.

Despite the challenges and the unknowns, we believe that it is in the best interest of the patients and the field to push the envelope of repair further by refining our surgical approaches using the mLV as the systemic pumping chamber and the MV as the systemic AV valve in ccTGA.

Conflict of Interest Statement

Authors have nothing to disclose with regard to commercial support.

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