Multimodality Imaging in Management of Adults with Dextro-Transposition of the Great Arteries Post Arterial Switch Operation

Desireé R. Conrad, MD, MA, Jennifer P. Woo, MD, George K. Lui, MD, and Daniel E. Clark, MD, MPH, *Palo Alto, California*

INTRODUCTION

Dextro-transposition of the great arteries (D-TGA) is a rare, cyanotic congenital heart disease that affects 3 in 10,000 births.[1] It accounts for approximately 5% of all congenital heart disease and is the second most common cyanotic heart disease, comprising 20% of cases. The most commonly associated lesion is ventricular septal defect (VSD), which occurs in 50% of patients. Other associated lesions are coronary variations, left ventricular (LV) outflow tract obstruction, coarctation, pulmonary outflow tract obstruction, and mitral and tricuspid valve abnormalities. Without surgical repair, D-TGA has a high infant mortality rate within the first week of life. Fortunately, however, there are excellent outcomes after surgical repair, specifically with the arterial switch operation (ASO), with 15- to 20-year survival rates $>95\%$.[2,3] Routine multimodality imaging with transthoracic echocardiography (TTE), cardiac computed tomography (CCT), and cardiovascular magnetic resonance (CMR) or magnetic resonance angiography (MRA) are complementary for surveillance of short- and long-term postoperative complications.[4] Long-term postoperative complications found in the adolescent and adult population include ventricular dilation and dysfunction, supravalvular pulmonary stenosis (PS), branch pulmonary artery (PA) stenosis secondary to LeCompte maneuver, neoaortic root dilation, neoaortic valve regurgitation, and coronary stenosis and/or obstruction.[5,6]

CASE PRESENTATION

A 26-year-old man with a history of D-TGA and a subarterial VSD underwent neonatal repair with patent foramen ovale closure, VSD closure, and ASO at 10 days old in another country without any reported complications. The patient had routine cardiology follow-up until the age of 21, when they moved to the United States, then reestablished care with our cardiology department at the age of 26. They reported fatigue, decreased exercise tolerance, and dyspnea with exertion and often felt that they could not keep up with friends. Vital signs were notable for heart rate 84 bpm, blood pressure 154/62 mm Hg, and SpO2 100%. A TTE was most notable for severe aortic regurgitation (AR) with holodiastolic flow reversal (HDFR) in the descending aorta and also revealed a mildly dilated neoaortic root (4.1 cm) and moderately dilated proximal ascending aorta (4.6 cm). The arch was not well visualized to rule out coarctation. The LV was normal size with mildly reduced systolic function LV ejection fraction (EF) of 51%. The TTE also showed moderate supravalvular neo-PS (peak/mean gradient 51/30 mm Hg), mild pulmonary regurgitation (PR), moderate tricuspid regurgitation, and mildly reduced RV systolic dysfunction. The patient was started on an angiotensin receptor blocker for hypertension and borderline ventricular dysfunction.

Exercise VO2 test was performed to assess functional capacity, but the test was suboptimal (respiratory exchange ratio 0.81) due to early termination after 7 minutes from severe exercise-induced hypertension (peak blood pressure, 246/82 mm Hg). It was notable for reduced VO2 23 mL/kg/min (45% predicted), 78% maximal predicted heart rate, and normal ventilatory efficiency (VE/VCO2 slope = 26.7). The suboptimal heart rate and inadequate respiratory exchange ratio limit the interpretation of these data.

Cardiovascular magnetic resonance was obtained to further interrogate the RV outflow obstruction, branch PAs, coronary ostial anastomoses, and aortic arch for associated coarctation, quantify valvular regurgitation, and confirm biventricular size/function. Cardiovascular magnetic resonance revealed patent right and left coronary arteries originating from the facing sinuses of Valsalva (Figure 1). There was mild biventricular enlargement (RV end-diastolic volume index 112 mL/m^2, LV end-diastolic volume index 116 mL/m^2) with low-normal RV EF of 46% and mildly reduced LV EF of 50%. The branch PAs were anterior to and draped over the aorta consistent with a history of LeCompte maneuver (Figure 2). There was mild neo-PS and mild supravalvular PS with a peak gradient of 30 mm Hg across the main PA (MPA) without evidence of branch PA stenoses along with mild neo-PR (Videos 1-3). The neo-AR was moderate with estimated regurgitant fraction 20% and HDFR in the descending aorta (Figure 3). The neoaortic root was mildly dilated, measuring approximately 38 mm. There was no coarctation. The tricuspid regurgitation was moderate with an estimated regurgitant fraction of 30%.

As may often be the case with eccentric AR, TTE and CMR were slightly discordant in their qualification of the degree of AR with severe AR noted on TTE and moderate AR on CMR. Four-dimensional (4D) flow imaging better characterized the location of RV outflow obstruction and found only combined moderate neo-PS and supravalvular PS. To reconcile the difference in degree of AR and to further characterize the supravalvular PS in the setting of symptomatic functional impairment, the patient was referred for a cardiac

From the Divisions of Cardiovascular Medicine and Pediatric Cardiology, Department of Medicine and Pediatrics, Stanford University School of Medicine, Palo Alto, California.

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Correspondence: Desireé R. Conrad, MD, MA, Stanford University School of Medicine, Division of Cardiovascular Medicine, 300 Pasteur Drive, CVRC Faulk, Palo Alto, CA 94305-5406. (E-mail: *drconrad@stanford.edu*).

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VIDEO HIGHLIGHTS

Video 1: CMR, balanced steady-state free precession sequence, RV 3-chamber view, demonstrates combined valvular and supravalvular PS with predominant dephasing jet appreciated in the supravalvular area.
Video 2: CMR, 4D flow, oblique sagittal, outflow tract view, demonstrates valvular/supravalvular PS (*bright red*) and AR.
Video 3: CMR, 4D flow, long-axis outflow tract view, demonstrates moderate valvular/supravalvular PS with peak velocity 3.1 m/sec, peak pressure gradient 38 mm Hg.
Video 4: Two-dimensional TTE, subcostal long-axis view of the LV outflow tract, aortic valve, and aortic root, demonstrates the neoaortic root and ascending aorta, but the dilation is out of plane.
Video 5: Two-dimensional TTE, subcostal long-axis view with color-flow Doppler, demonstrates AR.
Video 6: CMR, balanced steady-state free precession sequence, LV long-axis cine view, demonstrates the dilated neoaortic root with AR.
Video 7: CMR 4D flow, oblique sagittal aortic display, demonstrates HDFR (*vector arrows*) in the descending thoracic aorta.
Video 8: CMR, 4D flow, superior axial view of the branch PAs post LeCompte maneuver, demonstrates normal branch flow without stenosis.
Video 9: Two-dimensional TTE, high parasternal, basal short-axis view with color-flow Doppler of branch PAs post LeCompte maneuver, demonstrates incomplete visualization of the branch pulmonary arteries.

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catheterization. Notable findings included a combined gradient across the right ventricular outflow tract (RVOT) of 46 mm Hg (pullback from MPA to RV: MPA 28/12/20 mm Hg, supravalvular pulmonary root 64/12/35 mm Hg, RV 74/10 mm Hg), normal cardiac index (4.5 L/min/m^2), and low indexed pulmonary vascular resistance (2.2 WUi). Angiography was remarkable for moderate (2+) neo-AR, dilated aortic root, and no arch obstruction. Selective left and right coronary angiography demonstrated reimplanted right and left coronary arteries without stenoses. Right ventricular outflow tract angiogram demonstrated no PR with predominant supravalvular narrowing with the aforementioned gradient. Overall, cardiac catheterization demonstrated moderate neo-PS and moderate AR.

Ultimately our patient elected transcatheter intervention of the neopulmonary valve as the preferred option to defer surgical intervention. Repeat cardiac catheterization with balloon angioplasty of the supravalvular and valvar region of the MPA was then performed. Compared to the prior catheterization, the hypertension was better controlled, and consequently the total gradient across the RVOT was significantly reduced. After balloon angioplasty, the total gradient improved with no angiographic evidence of PR before or after balloon dilation of the RVOT.

Currently, the patient remains on an angiotensin receptor blocker with improved exercise tolerance and recovery of biventricular systolic function and is now able to run 2 to 3 miles without dyspnea.

DISCUSSION

Globally, a significant proportion of adolescents and young adults with congenital heart disease are lost to follow-up. Lack of surveillance monitoring of repaired congenital heart disease can lead to late detection of long-term postsurgical complications and increased mortality. Upon reestablishing care, it is important to obtain baseline imaging to confirm the anatomy and evaluate the stability of the surgical repair to determine the necessity and timing of reintervention. Transthoracic echocardiography remains the preferred initial diagnostic test.

According to the 2018 American Heart Association/American College of Cardiology (AHA/ACC) guideline for the management of adults with congenital heart disease (ACHD), interval follow-up is critical for monitoring common complications after ASO including supravalvular neo-PS, branch PA stenosis, neoaortic root dilation, neoaortic valve dysfunction, and ventricular dysfunction. As in this case, the development of supravalvular PS is the most common postoperative sequela, occurring in approximately 30% to 40% of patients,[5,7] with frequent need for intervention. Supravalvular PS is related to surgical technique and age at operation.[8] Risk factors for the development of supravalvular PS include pulmonary reconstruction with patches, aortic arch anomalies, and VSD.[9] Transthoracic echocardiogram is a good initial diagnostic test that can identify multilevel RVOT obstruction using a combination of continuous-wave and pulsed-wave Doppler. However, supravalvular PS may be difficult to accurately interrogate and quantify on TTE due to limitations assessing this postsurgical structure that is often immediately retrosternal. Additionally, branch PAs after the LeCompte maneuver are challenging to image since they are ellipsoid with reduced anteroposterior dimensions compared with superoinferior dimensions.[10] Multimodality imaging helps mitigate these limitations, as is demonstrated in this case. Initially, TTE imaging led the ACHD cardiologist to suspect the patient's symptoms were driven by the left-sided hemodynamic burden from AR. However, CMR imaging and 4D flow quantification helped reclassify the AR as moderate and focus attention on the residual right-sided lesions. Cross-sectional imaging with CMR or CCT augments noninvasive evaluation of RVOT obstruction by permitting three-dimensional (3D) reconstruction of levels of stenoses.[11] Moreover, CMR with 4D flow permits integration of hemodynamic information with the anatomical assessment without ionizing radiation exposure.[12]

Additionally, CMR is a complementary diagnostic tool for characterizing conotruncal defects as it offers multiplanar cine and flow imaging. Our patient's neoaortic root dilation is another common sequela of the ASO, occurring in approximately two-thirds of the population, with increased prevalence among those born with a VSD.[13] The neoaortic root in D-TGA post ASO requires lifelong monitoring as annual dilation is reported to be faster than that of the general population at a growth rate of 0.16 cm per year.[14] There is no consensus regarding elective aortic root replacement or neoaortic valve replacement versus repair after ASO. Fortunately, despite neoaortic root dilation and AR being common findings, the overall rate of aortic root and valve reintervention remains low given no identified increased risk of complications such as dissection or rupture beyond a certain diameter.[6] Thus, the timing and type of neoaorta and neoaortic valve reintervention should be individualized.

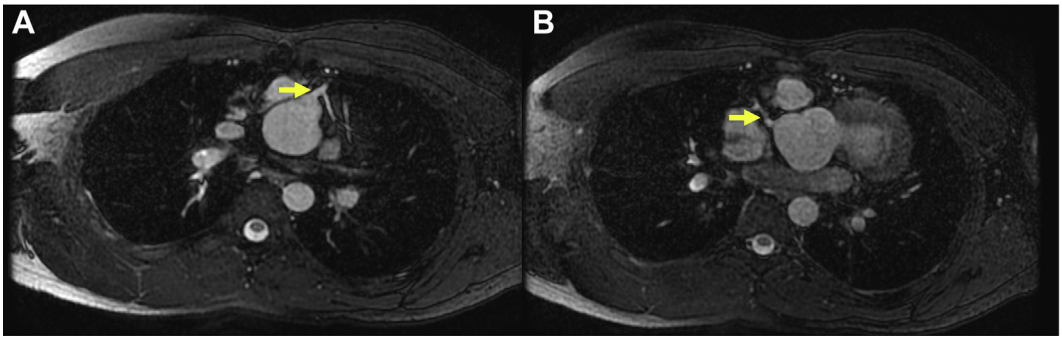

Figure 1 CMR, 3D whole-heart MRA (noncontrast, free-breathing, diaphragmatic, navigator sequence, with axial reconstruction) of the left main coronary artery **(A)** and right coronary artery **(B)**, demonstrates the origins of the reimplanted coronary arteries (*arrows*).

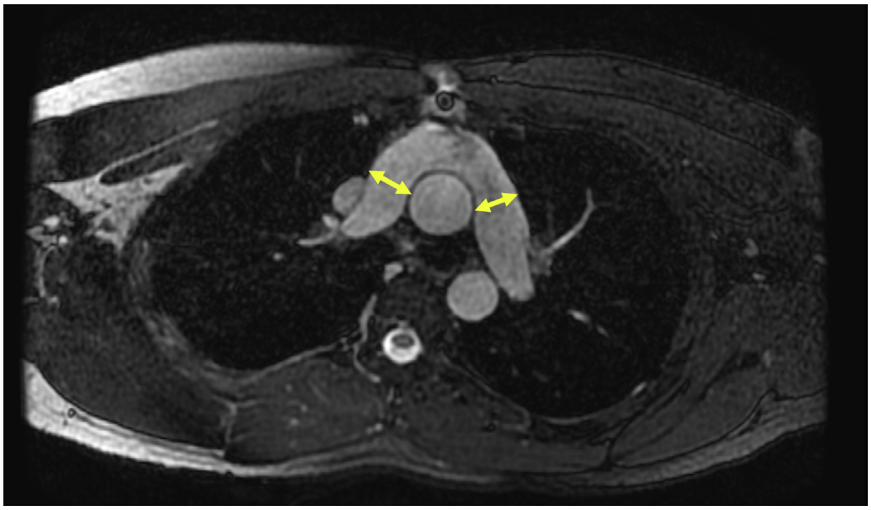

Figure 2 CMR, 3D whole-heart MRA (noncontrast, free-breathing, diaphragmatic, navigator sequence, with axial reconstruction), superior axial view, demonstrates the branch PAs post LeCompte maneuver draped over the aorta without significant anatomic narrowing.

Multimodality imaging can support the findings on TTE and further guide clinical decision-making by providing double oblique cross-sectional measurements of the neoaortic root, direct quantification of AR, and accurate phenotyping of its hemodynamic consequences with LV volumes, function, and tissue characterization (Figures 4 and 5).

The TTE identified neoaortic root and ascending aortic dilation via two-dimensional (2D) imaging planes (Figure 5, Videos 4 and 5). However, a limitation of TTE is that diameters are measured in a 2D oblique plane. Therefore, they are subjected to increased variance across serial measurements in repeat TTEs. Cardiac magnetic resonance imaging allows for the neoaortic root diameter to be measured in a double oblique plane allowing for more reliable 3D interpretation of the measurement.

Quantification of the severity of the neosemilunar valves' regurgitation differed between TTE, CMR, and cardiac catheterization. This difference is secondary to the imaging planes, eccentric direction of the jets (AR), and subsequent splaying of the jet deep in the cavity and the known discordance between modalities. The present case nicely illustrates how eccentric AR jets in the setting of conotruncal defects with aortic root dilation can be challenging to quantify on TTE with a tendency to be overestimated in severity. An advantage of CMR is that it offers the ability for direct quantification of semilunar valve regurgitation by 2D and/or 4D phase contrast imaging (Videos 6 and 7). Finally, the presence or absence of HDFR in the descending thoracic aorta has been shown to be a useful marker of AR severity and associated with adverse clinical outcomes.[15]

Multidisciplinary discussion initially concluded that elective surgical repair could be considered given the multivalvular lesions on TTE and decreased exertional tolerance; suggested repair would include neoaortic valve replacement, neopulmonary valvar and supravalvular repair, PA plasty, and tricuspid valve repair. However, the patient preferred to delay surgical repair and opted for transcatheter intervention of the neo-PS. The 2018 AHA/ACC guideline for the management of ACHD states catheter or surgical intervention for PS is reasonable in adults with D-TGA after ASO with symptoms of heart failure or decreased exercise capacity attributable to PS. Our TTE findings coupled with CMR quantification of the RVOT obstruction and the AR helped to guide this decision. While 2D TTE with color-flow Doppler suboptimally evaluated the branch PAs, CMR was able to confirm unobstructed PAs post LeCompte maneuver (Videos 8 and 9). Given the identification of predominantly supravalvular main

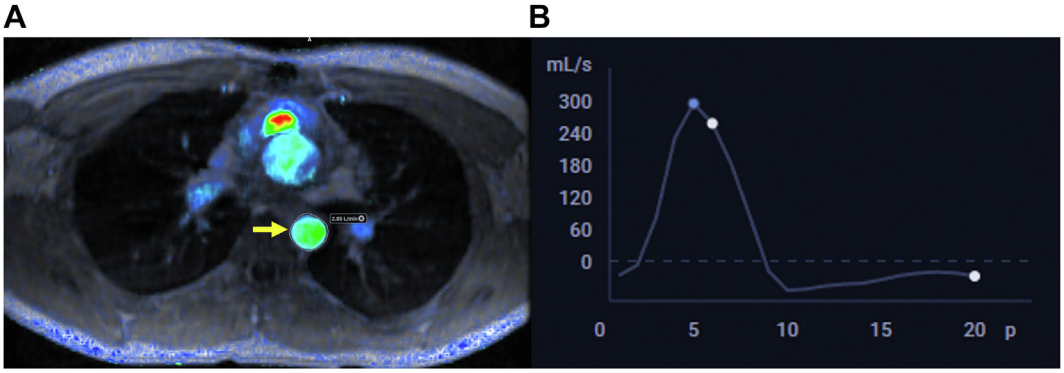

Figure 3 CMR, 4D flow, superior axial view **(A)** and time/volume curve analysis **(B)**, demonstrates HDFR in the descending thoracic aorta (*arrow*).

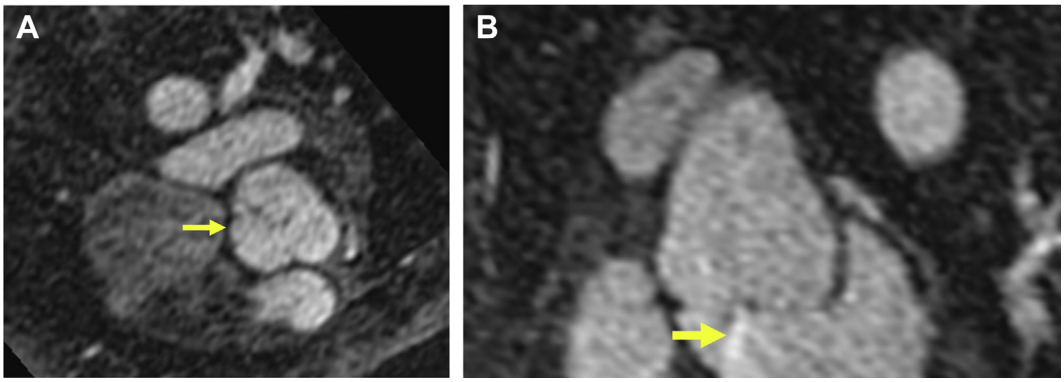

Figure 4 CMR 3D whole-heart MRA (noncontrast, free-breathing, diaphragmatic, navigator sequence, with axial reconstruction) acquired in diastole, en face view of the neoaortic valve **(A)** and oblique coronal view **(B)** of the neoaortic root, demonstrates prominent dephasing jet (*arrows*) angled toward the interventricular septum.

neo-PS on CMR, we proceeded with transcatheter balloon angioplasty to this region. Noninvasive CMR imaging also confirmed patent reimplanted coronary ostia, which helped with procedural planning for transcatheter intervention.

We are pleased with our patient's clinical improvement. We continue to monitor functional status, residual lesions, and associated hemodynamic consequences routinely with serial TTE complemented with occasional CMR. Given that the patient is ACHD anatomy class III and physiologic class C, we encourage annual surveillance visits with TTE and electrocardiogram and biannual visits with cardiopulmonary stress testing and CMR per the 2018 AHA/ACC guideline for the management of ACHD.[6]

CONCLUSION

Echocardiography remains an essential tool for routine surveillance of long-term complications following surgical repair of D-TGA post ASO. The addition of CMR helps further guide clinical decision-making with regards to timing of catheter or surgical intervention.

ETHICS STATEMENT

The authors declare that the work described has been carried out in accordance with The Code of Ethics of the World Medical Association (Declaration of Helsinki) for experiments involving humans.

CONSENT STATEMENT

Complete written informed consent was obtained from the patient (or appropriate parent, guardian, or power of attorney) for the publication of this study and accompanying images.

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SUPPLEMENTARY DATA

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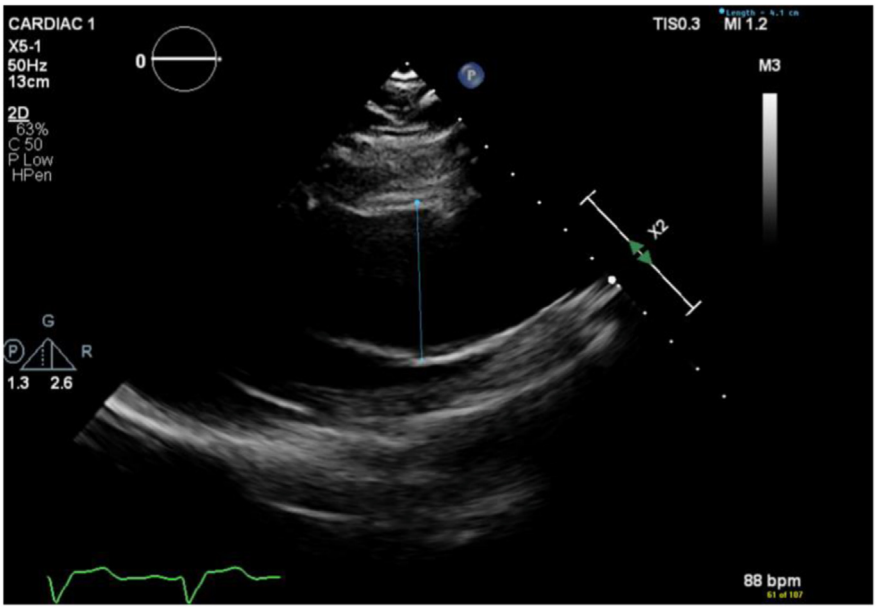

Figure 5 Two-dimensional TTE, parasternal long-axis view, demonstrates the dilated aortic root (measuring 41 mm).

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