Cardiac Magnetic Resonance to Evaluate Percutaneous Pulmonary Valve Implantation in Children and Young Adults

Experience with cardiac magnetic resonance to evaluate coronary arteries in children and young adult patients is limited. Because noninvasive imaging has advantages over coronary angiography, we compared the effectiveness of these techniques in patients who were being considered for percutaneous pulmonary valve implantation.

We retrospectively reviewed the cases of 26 patients (mean age, 12.53 ± 4.85 yr; range, 5–25 yr), all of whom had previous right ventricular-to-pulmonary artery homografts. We studied T2-prepared whole-heart images for coronary anatomy, velocity-encoded cine images for ventricular morphology, and function- and time-resolved magnetic resonance angiographic findings. Cardiac catheterization studies included coronary angiography, balloon compression testing, right ventricular outflow tract, and pulmonary artery anatomy.

Diagnostic-quality images were obtained in 24 patients (92%), 13 of whom were considered suitable candidates for valve implantation. Two patients (8%) had abnormal coronary artery anatomy that placed them at high risk of coronary artery compression during surgery. Twelve patients underwent successful valve implantation after cardiac magnetic resonance images and catheterization showed no increased risk of compression. We attempted valve implantation in one patient with unsuitable anatomy but ultimately placed a stent in the homograft.

Magnetic resonance imaging of coronary arteries is an important noninvasive study that may identify patients who are at high risk of coronary artery compression during percutaneous pulmonary valve implantation, and it may reveal high-risk anatomic variants that can be missed during cardiac catheterization. (Tex Heart Inst J 2018;45(2):63-9)

Percutaneous pulmonary valve implantation (PPVI) is a relatively new treatment option for patients with residual right ventricular outflow tract (RVOT) obstruction or dysfunction of right ventricle-to-pulmonary artery (RV–PA) homografts.1,2 The most prevalent congenital heart defects in those who undergo PPVI are tetralogy of Fallot, pulmonary atresia, truncus arteriosus, and ventricular septal defect with pulmonary stenosis or pulmonary atresia.3-7 However, PPVI has been associated with complications, such as bleeding, hematoma, stent fracture, and coronary artery (CA) compression, the last of which is among the most severe.8-10

Cardiac magnetic resonance (CMR) has increasingly been used to evaluate complex congenital heart conditions, either pre- or postoperatively, because patients are not exposed to ionizing radiation.11,11 In addition to producing high-quality diagnostic images of the pulmonary vasculature, RV volume, ventricular function, and outflow tract anatomy,14,15 CMR can detect the abnormal origin and proximal course of CAs, as well as coronary ectasias or aneurysms.15,24 In one report, CMR provided images of a potentially dangerous course of the left anterior descending CA in a patient with RVOT homograft dysfunction after a Ross-Konno operation.5

The purpose of our study was to determine whether CMR provides advantages over coronary angiography in evaluating coronary anatomy in young patients who are at high risk of CA compression during PPVI.

Patients and Methods

We retrospectively reviewed the cases of 26 pediatric and young adult patients (15 males; mean age, 12.53 ± 4.85 yr; range, 5–25 yr) who had congenital heart disease and had undergone RV–PA homograft placement (Table I). From September 2012 through September 2015, the patients underwent CMR evaluation in preparation for
The CMR studies included coronary anatomy evaluation by use of T2-prepared whole-heart images, velocity-encoded flow assessment, RVOT and PA evaluation by time-resolved MR angiography, and RVOT anatomy and RV function by delayed enhancement sequences and cine MR. We compared the findings on CMR to those obtained from cardiac catheterization procedures and previous cardiothoracic surgical reports, specifically CA anatomy, balloon testing for coronary compression, and RVOT and PA anatomy. Approval was obtained from the Driscoll Children’s Hospital Institutional review board.

All CMR studies were performed on an Ingenia 1.5T MR system (Koninklijke Philips N.V.). The studies were done without sedating patients, except for 6 children who were younger than 9 years of age. Studies were postprocessed on a satellite workstation (Circle Cardiovascular Imaging Inc.) and reviewed by an experienced cardiologist in charge of clinical CMR reporting.

Coronary Imaging Studies. Electrocardiogram-gated, respiratory-navigated, 3-dimensional steady-state free precession sequences were used to obtain T2-prepared whole-heart coronary images. The spatial resolution was isotropic, with slice thicknesses of 1.2 mm in young children (≤10 yr old) and 1.5 mm in older children and young adults (>11 yr old). The navigator window was set between 3 and 5 mm, depending on the age of the patient. Image acquisition duration was 60 ms in young children and 80 ms in older children and young adults. The trigger delay was adjusted to mid diastole to reduce the effect of cardiac motion; in younger children it was adjusted to early systole because of their faster heart rate. The heart rate varied with the age of the patient (70–100 beats/min in older children and young adults, and 110–130 beats/min in young children). The total duration of scanning was 8 to 10 min.

Cine Magnetic Resonance Imaging. Balanced steady-state free precession cine MR images were acquired to visualize the ventricular outflow tracts, and vertical long-axis, horizontal long-axis, and short-axis stack images were obtained to visualize both ventricles. Gradient turbo-field echo sequences were performed to reduce artifacts on images. Postprocessing techniques on an independent workstation (Circle Cardiovascular Imaging Inc.) included contouring cine images for volumetric analysis.

Time-Resolved Magnetic Resonance Angiography. Patients underwent noncardiac-gated, time-resolved angiography during breath-holds after injection of gadopentetate dimeglumine contrast medium at a dose of 0.02 mmol/kg of body weight at a rate of 2 mL/s. A total of 25 dynamic phases were acquired. Postprocessing techniques on an independent workstation included producing volume-rendered reconstructions.

Late Gadolinium-Enhanced Imaging. Two-dimensional phase-sensitive inversion recovery sequences with gadolinium-enhanced MR imaging were obtained, after intravenous injection of gadopentetate dimeglumine, by using T1-weighted imaging in the cardiac short-axis and 4-chamber views. No extra dose of gadolinium was used. The time between contrast injection and delayed-enhancement study was 10 min. The Look-Locker technique was used to obtain inversion times for optimal suppression of the normal myocardial signal.

Flow Assessment. A free-breathing, velocity-encoded, phase-contrast sequence with a temporal resolution of 30 frames per cardiac cycle was used to evaluate flow in the pulmonary homograft, branch PAs, and aortic root. Velocity encoding was set at 150 cm/s for normal pulmonary and aortic roots; in stenosed homografts with aliasing, velocity encoding was increased until no aliasing was seen. Echocardiographic peak velocity was also used as a guide to set velocity encoding in patients who had echocardiographic evidence of homograft stenosis. In patients with clinical indications, ventricular inflows were also evaluated. Slice position and velocity encoding were optimized by using 2 orthogonal views of the blood vessels. Postprocessing techniques on an independent workstation included contouring phase-contrast flow images.

Percutaneous Pulmonary Valve Implantation. Cine MR images were used to measure pulmonary annulus size, and the findings agreed well with those obtained on cardiac catheterization. A Melody® Transcatheter Pulmonary Valve (Medtronic, Inc.) was deployed in each patient. The device consists of a valve—harvested from a bovine jugular vein—sutured into a platinum-iridium stent frame (length, 28 mm; diameter, 18 mm). The stent is crimped onto an Ensemble® Transcatheter Delivery System (Medtronic) and can be expanded up

| Table I. Characteristics of the 26 Patients |
|------------------------------------------|
| Variable                  | Value               |
|---------------------------|---------------------|
| Age (yr)                  | 12.53 ± 4.85 (5–25) |
| Sex                       |                     |
| Males                     | 15                  |
| Females                   | 11                  |
| Diagnosis                 |                     |
| Tetralogy of Fallot       | 14 (53.8)           |
| Truncus arteriosus        | 4 (15.4)            |
| Double-outlet right ventricle | 2 (7.7)          |
| Aortic stenosis           | 2 (7.7)             |
| Coarctation of aorta      | 2 (7.7)             |
| Pulmonary stenosis or atresia | 2 (7.7)        |

Data are expressed as mean ± SD and range or as number and percentage.
to 22 mm in diameter. The stent is designed for balloon-in-balloon deployment, and outer balloon sizes of 18, 20, and 22 mm are available.

Results

Coronary Artery Evaluation

Diagnostic-quality images were obtained in 24 of 26 patients (92%). In 2 patients, the branches of the left CA were not well visualized because of stent artifact in the branch PAs with signal dephasing.

An anomalous CA origin was found in 4 patients (15.4%). Two of these patients had unfavorable CA anatomy, which placed them at high risk of CA compression during PPVI. One had mirror-image dextrocardia and a double-barrel RVOT, in addition to an anomalous course of the right CA (RCA), which ran between the native aortic root and RV–PA homograft (Fig. 1). In the other patient, the RCA arose from the left coronary sinus and coursed between the RVOT and aortic root. The remaining 2 patients with an anomalous CA origin were at no increased risk of compression during PPVI. In one, the anomalous left CA took a retro-aortic course (Fig. 2). In the other, the RCA arose from the left CA and took a retro-aortic course.

Subsequent catheterization angiographic studies were done in all subjects, including selective CA angiography to confirm the results found on CMR. In patients not at increased risk of CA compression by CMR, RVOT balloon angioplasty testing across the homograft was performed to confirm the CMR findings. As expected, no obvious compression was noted in these patients.

Percutaneous Pulmonary Valve Implantation

After extensive review of the patients’ angiographic and CMR studies, 13 of the 22 patients (59%) were considered ideal candidates for PPVI according to the American Heart Association (AHA) criteria and underwent the procedure. The indications for PPVI were significant pulmonary homograft stenosis or homograft valve regurgitation with clinically significant RV hypertrophy or dilation, as interpreted by the cardiologist in charge of clinical patient care. Nine of the 22 patients did not meet AHA criteria for PPVI or were at high risk of CA compression; these included the 2 patients with an anomalous CA origin who were not at increased risk of compression, as well as the 2 patients who had a double-barrel outflow tract.

One patient had severe RVOT aneurysms with severe kinking of the pulmonary homograft, and the findings on CMR predicted a high degree of difficulty for PPVI. Nevertheless, the patient underwent the procedure because of significant homograft insufficiency and stenosis. Ultimately, the valve could not be deployed because of technical difficulty, so the patient had a bare-metal stent placed in the RV–PA homograft (Fig. 3).

A successful PPVI was performed in 12 of the 13 patients who underwent the procedure (Fig. 4).

Right Ventricular and Homograft Characteristics

Cardiac magnetic resonance RV–PA homograft data were available for 22 patients (Table II): 18 patients had...
homograft insufficiency and 16 had homograft stenosis. The mean RV–PA homograft flow (not indexed to body surface area) was $5.03 \pm 2.3$ L/min, and the mean RV–PA homograft regurgitant fraction was $21.54\% \pm 13.14\%$. The mean net fractional branch-PA flow distribution was 47% to the right PA and 53% to the left PA.

We observed RV wall motion abnormalities with hypokinesis of the RV anterior wall at the insertion site of the homograft in 14 patients. One of these patients also had paradoxical motion of the interventricular septum in systole.

Table III shows mean ventricular volumes normalized for body surface area categorized by sex. To make our data comparable to previously published normalized values, we removed our only patient older than 20 years for this particular set of results. We found a large gradient between the mean RV end-diastolic volume in our female ($82 \pm 32$ mL/m$^2$) and male ($107 \pm 23$ mL/m$^2$) patients in comparison with that in healthy female ($76 \pm 9$ mL/m$^2$) and male ($84 \pm 12$ mL/m$^2$) subjects. This was also true for the mean RV end-systolic volume. The RV ejection fraction was lower in our male patients ($0.54 \pm 0.08$) than in healthy male children ($0.62 \pm 0.04$); it remained within the normal limits in our female patients ($0.58 \pm 0.09$) compared with that in healthy female children ($0.63 \pm 0.04$).

**Fig. 3** A) Steady-state free precession cardiac magnetic resonance image (CMR) and B) coronary angiogram show severe kinking of a homograft (double arrow) and a right ventricular (RV) outflow aneurysm (arrow) in a 12-year-old girl with tetralogy of Fallot after right ventricle-to-pulmonary artery homograft placement. The CMR predicted the technical difficulty encountered during an attempt to implant a percutaneous pulmonary valve.

**Fig. 4** A) T2-preparation whole-heart cardiac magnetic resonance image shows coronary arteries (arrows) arising from the native aortic root (NAo), far from the pulmonary homograft (PA), in an 18-year-old man with double-outlet right ventricle and dextro-malposed great arteries and subaortic stenosis after a Damus-Kaye-Stansel procedure. B) Coronary angiogram confirms the anatomic findings. The patient underwent successful percutaneous pulmonary valve implantation without coronary artery compression.

NeoAo = neoorta
Discussion

Percutaneous pulmonary valve implantation has proved to be highly effective in restoring RV–PA homograft function and improving ventricular function, albeit with some severe complications, such as stent fracture and CA compression.¹⁻⁴ Before and after PPVI, patients must undergo multiple imaging studies to evaluate their complex heart and vascular anatomy, some of which expose patients to ionizing radiation.⁵,⁶ Cardiac MR has proved to be an excellent alternative, providing high-yield results in both young and adult patients.¹¹,¹² Many investigators have shown its high quality and accuracy in describing and evaluating cardiac anatomy, ventricular function, major vessel anatomy, and the origin and proximal course of anomalous CAs, even in cases when diagnosis with x-ray coronary angiography is difficult.¹³,¹⁹⁻²⁴

In our study, 2 patients were at high risk of CA compression during PPVI, which is similar to the numbers documented in other studies.¹¹,²⁴ Morray and colleagues⁴⁶ reported that 5% of patients who underwent cardiac catheterization for possible PPVI were found to have CA compression on RVOT balloon angioplasty testing. Of our final 13 candidates, 12 underwent successful PPVI after CMR showed no coronary abnormalities that would place them at high risk of intraprocedural CA compression. No obvious compression of CAs was observed in any of the patients during their elective CA angiogram with balloon testing across the homograft. We identified no major differences between the findings on CMR and cardiac catheterization studies. Of note, in the patient who had an unsuccessful PPVI, CMR had shown the procedure to be unfeasible because of severe RVOT aneurysm and severe kinking of the pulmonary homograft. These findings were not clearly detected on pre-PPVI cardiac catheterization.

Of the 4 patients with anomalous CA origins, 2 had a retro-aortic course of the anomalous CA, which would not have increased the risk of CA compression during PPVI. We found no evidence of proximal CA kinking or ectasia in our study population.

Diagnostic-quality CMR images were obtained in 24 patients (92%). Images from the other 2 patients were

| TABLE II. RV–PA Homograft Characteristics and Hemodynamic Findings in 22 Patients |
|-----------------------------------------------|
| Variable                        | Value                  |
| Homograft characteristics       |                        |
| Insufficiency                   | 18 (82%)               |
| Stenosis                        | 16 (73%)               |
| RV regional wall abnormalities  | 14 (64%)               |
| Heart rate (beats/min)          | 83 ± 14                |
| Homograft total flow (L/min)    | 5.03 ± 2.3             |
| Homograft regurgitant fraction (%) | 21.54 ± 13.14       |
| Right PA flow (%)               | 47 ± 17                |
| Left PA flow (%)                | 53 ± 17                |

PA = pulmonary artery; RV = right ventricle

Data are expressed as number and percentage or as mean ± SD.

| TABLE III. Ventricular Volumes Normalized for Body Surface Areaa |
|---------------------------------------------------------------|
| Variable       | Males | Females |
|                | Current Study | Healthy Childrenb | Current Study | Healthy Childrenb |
| Age (yr)       | 13.25 ± 5     | 8 to 17           | 11.22 ± 2     | 8 to 17           |
| RV-EDV (mL/m²) | 107 ± 23      | 84 ± 12           | 82 ± 32       | 76 ± 9            |
| LV-EDV (mL/m²) | 78 ± 12       | 80 ± 12           | 68 ± 17       | 75 ± 10           |
| (n=14)         |              |                   | (n=11)        |                   |
| RV-ESV (mL/m²) | 51 ± 19       | 32 ± 7            | 35 ± 14       | 27 ± 5            |
| LV-ESV (mL/m²) | 32 ± 5        | 28 ± 6            | 26 ± 8        | 25 ± 5            |
| (n=12)         |              |                   | (n=9)         |                   |
| RV-EF          | 0.54 ± 0.08   | 0.62 ± 0.04       | 0.58 ± 0.09   | 0.63 ± 0.04       |
| LV-EF          | 0.61 ± 0.04   | 0.66 ± 0.05       | 0.61 ± 0.06   | 0.63 ± 0.06       |
| (n=13)         |              |                   | (n=10)        |                   |

EDV = end-diastolic volume; EF = ejection fraction; ESV = end-systolic volume; LV = left ventricular; RV = right ventricular

aThis analysis included 21 patients. We excluded the one patient who was older than 20 years.
bNormalized values by body surface area obtained by cardiac magnetic resonance in healthy children.²⁷

Data are expressed as mean ± SD.
suboptimal because of stent artifact in the branch PAs, with signal dephasing.

The chief underlying diagnosis in our patients was tetralogy of Fallot, a condition often repaired with RV–PA homografts. Of note, 2 of our patients had a double-barrel outflow tract. They did not undergo PPVI because they would have been at high risk of CA compression.

Although our study's main focus was CA anatomy, we also obtained useful data on RV volume and homograft flow characteristics. The mean RV volume in our female patients was higher than that reported in healthy female children, and it was in the upper limit. In our male patients, the mean RV volume was beyond the upper limit, and the mean RV ejection fraction was below the lower limit of those in healthy male children. Although previous study results have shown that sex differences are more marked in older children in regard to volume, there was still a large difference in RV end-diastolic volume, end-systolic volume, and ejection fraction between our patients and healthy children. Of note, left ventricular volume and ejection fraction were not substantially different from those reported in healthy children. We suspect that these findings are related to the large percentage of homograft insufficiency and stenosis in our patient population but do not account for the large gradients seen, especially because the mean homograft regurgitant fraction was only 21.54 ± 13.14, which is considered to be mild.26

Limitations of the Study. Although our study was limited by a small sample size at a single institution, other CMR studies in similar groups of patients have presented comparable numbers of subjects.22–24

Conclusion. Coronary angiography with x-ray is considered the gold standard for detecting the risk of CA compression in patients undergoing PPVI. However, CMR has increasingly proved useful for evaluating RVOT and CA anatomy, and it may be more effective than standard coronary angiography in identifying CA courses that can place patients at high risk of compression during PPVI or in visualizing other conditions that would increase the technical difficulty of the procedure. In our study, CMR enabled comprehensive evaluation of CA anatomy. Larger prospective studies are needed to fully evaluate its role in patients undergoing PPVI.

References

1. Khambadkone S. Percutaneous pulmonary valve implantation. Ann Pediatr Cardiol 2012;5(1):53–60.
2. Alkashkari W, Cao QL, Kavinsky CJ, Hijaji ZM. Percutaneous pulmonary valve implantation for RVOT defects. Cardiac Interv Today 2010;4(5):21-29. Available at: http://cititoday.com/pdfs/cit0910_yu_Hijazi.pdf.
3. Dearani JA, Danielson GK, Puga FJ, Schaff HV, Warnes CW, Driscoll DJ, et al. Late follow-up of 1095 patients undergoing operation for complex congenital heart disease utilizing pulmonary ventricle to pulmonary artery conduits. Ann Thorac Surg 2003;75(2):399–411.
4. Poynter JA, Elghaedy P, McCrindle BW, Walters HL, 3rd, Kirshbom PM, Blackstone EH, et al. Association of pulmonary conduit type and size with durability in infants and young children. Ann Thorac Surg 2013;95(5):1605–702.
5. Wagner R, Daehnert I, Lurtz P. Percutaneous pulmonary and tricuspid valve implantations: an update. World J Cardiol 2015;7(4):167–77.
6. Lurtz P, Coats L, Khambadkone S, Nordmeyer J, Boudjemline Y, Schievano S, et al. Percutaneous pulmonary valve implantation: impact of evolving technology and learning curve on clinical outcome. Circulation 2008;117(15):1964–72.
7. Borik S, Crea A, Horlick E, Osten M, Lee K, Chaturvedi R, et al. Percutaneous pulmonary valve implantation: 5 years of follow-up: does age influence outcomes? Circ Cardiovasc Interv 2015;8(2):e001745.
8. Goreczny S, Eicken A, Ewert P, Morgan GJ, Fratz S. A new strategy to identify potentially dangerous coronary arterial patterns before percutaneous pulmonary valve implantation. Postepy Kardiol Interwencyjnej 2014;10(4):294–7.
9. Sridharan S, Coats L, Khambadkone S, Taylor AM, Bohnhoefer P. Images in cardiovascular medicine. Transcatheter right ventricular outflow tract intervention: the risk to the coronary circulation. Circulation 2006;113(25):e345–6.
10. Murray BH, McElhinney DB, Cheatham JP, Zahn EM, Berman DP, Sullivan PM, et al. Risk of coronary artery compression among patients referred for transcatheter pulmonary valve implantation: a multicenter experience. Circ Cardiovasc Interv 2013;6(5):535–42.
11. Rao UV, Vanajakshamma V, Rajasekhar D, Lakshmi AY, Reddy RN. Magnetic resonance angiography vs. angiography in tetralogy of Fallot. Asian Cardiovasc Thorac Ann 2013;21(4):418–25.
12. Geva T, Greil GF, Marshall AC, Landzberg M, Powell AJ. Gadolinium-enhanced 3-dimensional magnetic resonance angiography of pulmonary blood supply in patients with complex pulmonary stenosis or atresia: comparison with x-ray angiography. Circulation 2002;106(4):473–8.
13. Valsangiacomo Buchel ER, DiBernardo S, Bauersfeld U, Berger F. Contrast-enhanced magnetic resonance angiography of the great arteries in patients with congenital heart disease: an accurate tool for planning catheter-guided interventions. Int J Cardiovasc Imaging 2005;21(2-3):313–22.
14. Helbing WA, de Roos A. Clinical applications of cardiac magnetic resonance imaging after repair of tetralogy of Fallot. Pediatr Cardiol 2000;21(1):70–9.
15. Srinivas B, Patnaik AN, Rao DS. Gadolinium-enhanced three-dimensional magnetic resonance angiographic assessment of the pulmonary artery anatomy in cyanotic congenital heart disease with pulmonary stenosis or atresia: comparison with cineangiography. Pediatr Cardiol 2011;32(6):737–42.
16. Ntsinjana HN, Hughes ML, Taylor AM. The role of cardiovascular magnetic resonance in pediatric congenital heart disease. J Cardiovasc Magn Reson 2011;13:51.
17. Kellenberger CJ, Yoo SJ, Buchel ER. Cardiovascular MR imaging in neonates and infants with congenital heart disease. Radiographics 2007;27(1):5–18.
18. Boechat MJ, Ratib O, Williams PL, Gomes AS, Child JS, Alладa V. Cardiac MR imaging and MR angiography for assessment of complex tetralogy of Fallot and pulmonary atresia. Radiographics 2005;25(6):1535–46.
19. Mavrogenis S, Markoussis-Mavrogenis G, Kolovou G. Contribution of cardiovascular magnetic resonance in the evaluation of coronary arteries. World J Cardiol 2014;6(10):1060–6.
20. Post JC, van Rossum AC, Bronzwaer JG, de Cock CC, Hoffman MB, Valk J, Visser CA. Magnetic resonance angiography
of anomalous coronary arteries. A new gold standard for delineating the proximal course? Circulation 1995;92(11):3163-71.

21. Keegan J. Coronary artery wall imaging. J Magn Reson Imaging 2015;41(5):1190-202.

22. McConnell MV, Ganz P, Selwyn AP, Li W, Edelman RR, Manning WJ. Identification of anomalous coronary arteries and their anatomic course by magnetic resonance coronary angiography. Circulation 1995;92(11):3158-62.

23. Taylor AM, Thorne SA, Rubens MB, Jhooti P, Keegan J, Gatehouse PD, et al. Coronary artery imaging in grown up congenital heart disease: complementary role of magnetic resonance and x-ray coronary angiography. Circulation 2000;101(14):1670-8.

24. Taylor AM, Dymarkowski S, Hamaekers P, Razavi R, Gewillig M, Mertens L, Bogaert J. MR coronary angiography and late-enhancement myocardial MR in children who underwent arterial switch surgery for transposition of great arteries. Radiology 2005;234(2):542-7.

25. Taylor AJ, Salerno M, Dharmakumar R, Jerosch-Herold M. T1 mapping: basic techniques and clinical applications. JACC Cardiovasc Imaging 2016;9(1):67-81.

26. Feltes TF, Bacha E, Beekman RH 3rd, Cheatham JP, Feinstein JA, Gomes AS, et al. Indications for cardiac catheterization and intervention in pediatric cardiac disease: a scientific statement from the American Heart Association. Circulation 2011;123(22):2607-52.

27. Kawel-Boehm N, Maceira A, Valsangiacomo-Buechel ER, Vogel-Claussen J, Turkbey EB, Williams R, et al. Normal values for cardiovascular magnetic resonance in adults and children. J Cardiovasc Magn Reson 2015;17:29.