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# Cardiac magnetic resonance imaging and computed tomography for the pediatric cardiologist

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#### ABSTRACT

This review aims to provide an introduction to axial imaging, focusing on the basic physics, mode of acquisition and applications of magnetic resonance imaging and computed tomography in pediatric cardiology. Cardiac magnetic resonance imaging provides excellent assessment of ventricular size and function. Ventricular volumes together with phase contrast imaging provide important information about systemic flow, pulmonary flow, shunt volumes and regurgitant fraction. Three dimensional reconstructed images obtained by specific sequences as described in this review can be used to visualize detailed anatomy in palliated congenital heart disease while late gadolinium enhancement provides assessment of scar burden. Advanced modalities like four dimensional flow, parametric mapping, feature tracking and computational models have been briefly described.

Due to excellent spatial resolution, cardiac computed tomography is increasingly used to evaluate coronary anatomy and complex anatomy in single ventricle patients. It offers the advantage of simultaneously assessing the airway and vasculature in neonates with arch anomalies. The technical basics of the scan and timing of administration of contrast have been briefly described.

The safety profile of gadolinium based contrast agents in cardiac magnetic resonance imaging and radiation exposure in cardiac computed tomography has been highlighted. Both are complementary modalities, serving as an important diagnostic tool in the management of patients with congenital heart disease.

As magnetic resonance imaging (MRI) and computed tomography (CT) technologies have improved, utility in patients with acquired and congenital heart disease has grown. These technological advancements have occurred contemporaneously with the growth in the adult congenital population. In this review article, we aim to cover the basics of cardiac MRI and CT including frequently used sequences, common indications, modality specific safety and patient concerns, and emerging technologies.

#### 1. Cardiac magnetic resonance imaging (cMRI)

Sir Peter Mansfield and Paul Lauterbur jointly won the Nobel Prize in physics in 2003 for their pioneering work in magnetic resonance to create an image roughly fifty years ago [1]. Since then, rapid advances in both MRI hardware and software have made cMRI an important tool in the management of patients with congenital heart disease.

#### 1.1. The MRI machine

The MRI machine consists of a bore that houses the main magnet contributing to the static magnetic field. Magnetic field strength is measured in Tesla (T). 1 T is approximately 20,000 times the Earth's magnetic field. Clinically used scanner strengths are most commonly 1.5 T and 3 T. In practice, 1.5 T magnets are most commonly used in congenital heart disease and pediatrics due to increased artifact at higher field strengths. This static magnetic field is always turned on, a critical safety concern. A reference co-ordinate system in three orthogonal planes, x, y and z, is used to denote the direction of the magnetic field. By convention, the z axis is chosen parallel to direction of the scanner's magnetic field. Gradient coils in each of the orthogonal axes can generate a magnetic field along the corresponding axes when turned on. They are often in pairs to create linear spatial variation in the field. These gradient fields are superimposed on the static magnetic field to create a net magnetic field that is either augmented or decreased in the direction of the applied gradient. Radiofrequency

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transmitter coils are smaller coils within the gradient coils with amplitudes much smaller than other coils and oscillate in the megahertz range (MHz). They are placed closest to the patient's body. For cardiac imaging, a special receiver coil is placed over the chest to maximize signals emitted from the heart [2].

#### 1.2. Generation of the magnetic resonance image

Any atomic nucleus has protons and neutrons that have magnetic fields due to their charge and spin properties. However, only elements with an odd number of protons and neutrons exhibit a magnetic moment associated with their net spin. The hydrogen proton due to its abundance as a constituent of both water and fat molecules renders itself to be an ideal choice for MRI. Normally protons are randomly oriented in tissues such that the net magnetization of the sample is zero. On application of an external magnetic field, nuclear spins align themselves in the direction of this applied field. Each of these protons will precess, akin to a spinning top, around the direction of the applied field with a frequency proportional to the field strength.

Before a radiofrequency pulse is switched on, the net magnetic field is aligned with the static magnetic field. With a radiofrequency pulse, the net magnetization plane changes and precesses around the static field plane at an angle. The greater the amount of energy applied for a radiofrequency pulse, the greater the angle of change. Inhomogeneity caused by gradient coils causes spins to resonate at different frequencies such that only protons spinning at the same frequency to the applied radiofrequency pulse will respond. This property is used to select a tissue slice of interest, applying a gradient such that it resonates at the same frequency of the initial radiofrequency pulse but perpendicular to it. Finally, K space or Fourier space is a mathematical tool that transforms frequency data into spatial data. The faster the K space is filled, the faster an image is generated [3].

#### 1.3. Common sequences used in cardiac MRI (cMRI)

#### 1.3.1. Structural pulse sequences

1.3.1.1. Spin echo. Spin echo sequences or turbo spin echo are typically used prior to administration of gadolinium contrast. They are often termed simply black blood images as blood appears black and surrounding tissues appear as varying shades of grey (Fig. 1A). Their gated acquisition during the cardiac cycle minimizes cardiac motion. These sequences are less prone to metallic artifacts [4,5], commonly seen in repaired congenital heart disease like sternal wires, stents, septal occluders, etc. T1 and T2 weighting can be done depending on the tissue of interest. Typically one R-R interval is used in adults; however, in children, higher heart rates decrease the time between

image acquisitions required for longitudinal magnetization recovery leading to poor image quality. This is often avoided by having image acquisition occur over 3–4 RR intervals [4].

1.3.1.2. Gradient echo. Colloquially referred to as bright blood imaging because blood appears bright relative to surrounding tissue (Fig. 1B). This sequence is electrocardiographically (ECG) gated and acquires multiple images throughout the cardiac cycle resulting in a movie clip or 'cine' [6]. It provides valuable information of both anatomy and function of atrioventricular valves, semilunar valves and ventricles. Breathing artifacts are reduced by breath holds or by using multiple signal averages in the free breathing patient. The standard spoiled gradient echo pulse has been increasingly replaced by steady state free precession (SSFP) sequences that are considered the workhorse of cMRI. Being less sensitive to valve stenotic or regurgitant jets and ability to provide superior contrast between blood pool and myocardium, SSFP offers a definite advantage over spoiled gradient echo sequences [4]. Disadvantages include increased susceptibility to artifacts caused by suboptimal shimming or metallic devices.

1.3.1.3. Contrast enhanced magnetic resonance angiogram (MRA). Gadolinium based contrast is administered prior to acquisition of data to decrease the T1 relaxation time of blood so that it appears bright [7]. The dataset is a full volume set consisting of contiguous slices allowing for extensive post processing such as multiplanar reformatting (MPR), maximum intensity projection (MIP) images, and three dimensional (3D) reconstruction [8]. Timing of acquisition after contrast administration is key and is tailored to the vessel or structure of interest. The scan delay time should equal the contrast time for optimal vessel enhancement [9]. This is a non-ECG gated sequence where images are reconstructed as an average over the cardiac cycle leading to blurring of pulsatile structures like the aortic root [7] and are intended for primarily extracardiac morphology. With breath holding techniques to improve spatial resolution in small children, MRA has become an important tool to diagnose and follow vascular disease in children, often avoiding the need for frequent catheterizations [7,10].

1.3.1.4. Three dimensional (3D) SSFP. 3D SSFP sequence is an ECG triggered pulse sequence. Additionally, respiratory motion can be compensated for by using diaphragmatic navigators. They are obtained either before or after contrast administration and provide high resolution 3D datasets of both intracardiac and thoracic vasculature as data is obtained isotropically and flow independently [11]. Multiple post processing options are thus available for 3D visualization (Fig. 1C). Due to both respiratory navigation and



Fig. 1. A. Spin echo (black blood imaging) showing ascending aortic dilation B. Gradient echo (bright blood imaging) demonstrating bilateral superior venae cavae C. 3D SSFP data for 3D printing demonstrating extent of LV apical aneurysm {superior vena cava (SVC), Main pulmonary artery (MPA), Dilated Ascending aorta (Asc Ao), Descending Aorta (DAO), Left Ventricle (LV)}



Fig. 2. 2 A and B: Phase and magnitude image on phase contrast (PC) imaging. 2C and D Left ventricle (LV) and Right ventricle (RV) endocardial contours for volumetric analysis and ejection fraction. Epicardial (green) contours for LV mass.

cardiac gating, intracardiac structures like coronaries and aortic root can be well visualized [12].

#### 1.3.2. Functional or volumetric sequences

1.3.2.1. Phase contrast. Phase contrast magnetic resonance (PC-MR) imaging (Fig. 2A and B) is a technique to measure regional blood flow based on the concept that hydrogen nuclei flowing through a magnetic field accumulate a predictable phase in their spin that is proportional to the velocity. It produces a magnitude image and a phase image. On the phase image, the intensity of each pixel within the lumen is proportional to the velocity of blood at that location [13]. It is noninvasively used to calculate flow through a vessel, without the errors of assumption commonly seen with conventional Fick's methodology [13,14] in the catheterization laboratory. This is obtained by planning a slice perpendicular to the vessel of interest and contouring the vessel in cross section for the area. This is multiplied by the predetermined encoding velocity for flow measurements, typically set 25% above the expected maximum velocity [4]. Similar to echocardiography, aliasing occurs if the encoding velocity is much lower than the expected velocity in which case, it must be rescaled.

1.3.2.2. *Cine SSFP*. Balanced SSFP is the workhorse of cMRI as this sequence is used for assessment of ventricular volumes, ventricular mass, and ejection fraction. Retrospective ECG gating is preferred so that the entire portion of the diastolic cycle is evaluated. Though typically performed with breath holds, this can also be done with free breathing using multiple signal averages [4].

Imaging planes are easily obtained and mimic standard

echocardiographic views. These often include four-chamber or horizontal long axis two-chamber or vertical long axis, three camber, and short axis. Prescription of the ventricular short axis plane is variable with some centers performing it parallel to the atrioventricular valves and some parallel to the ventricular septum, with particular consideration to extend the slices beyond the level of the atrioventricular valves to capture the full extent of the right ventricle. Measurements are typically performed in the short axis plane. End-systolic volumes, enddiastolic volumes, ejection fraction and mass of both the ventricles are measured by contouring the epicardial and endocardial borders at endsystole and end-diastole [7] (Fig. 2C and D).

#### 1.3.3. Tissue characterization

*1.3.3.1. Myocardial perfusion.* This imaging enables visualization of the entry of contrast into the myocardium. Areas of decreased perfusion remain dark relative to areas of normal perfusion. When performed under pharmacological stress, it can delineate areas of ischemia [7, 15].

1.3.3.2. Late gadolinium enhancement (LGE). These sequences are often vendor and center specific but the goal is to identify regions of myocardial fibrosis. In general, these sequences are obtained 10–20 min after contrast administration. Adding an inversion pulse prior to the standard pulse sequence improves contrast between normal and abnormal myocardium [4]. An inversion time is selected at a time where the normal myocardium is uniformly nulled by manually choosing a time, using a TI scout or look locker sequence or using a standardized phase sensitive inversion recovery sequence. This is a cardiac gated sequence to minimize cardiac motion and often



Fig. 3. 3 A: Still image of cine SSFP Asymmetric septal hypertrophy (\*) in hypertrophic cardiomyopathy B. LGE positive area in HCM indicative of fibrosis C. 3D MRA demonstrating the LeCompte anastomosis post arterial switch procedure D. 3D SSFP showing RV-PA conduit

preferably breath-held with similar planes as the initial cine images used during ventriculography to aid comparison. Areas of myocardial fibrosis appear bright while normal myocardium appears dark because of the difference in how long contrast remains in healthy versus fibrotic tissue. E.g. LGE positive in hypertrophic cardiomyopathy (HCM) (Fig. 3A and B).

#### 1.4. Indications for cMRI

Contemporary indications for cMRI include essentially all forms of acquired and congenital heart disease regardless of age. As cMRI is limited in coronary artery assessment, computed tomography angiogram (CTA) is often preferable for dedicated coronary imaging. In the acutely ill or unstable patient, CTA is also preferable for defining vascular anatomy. Because of the speed of modern cardiac CTA and success of radiation dose reduction techniques, CTA is also often preferred for definition of vascular anatomy in cases where patients have increased anesthesia risk or clinical questions are related primarily to vascular anatomy. Of course, if a patient has a true contraindication to entering the MRI scanner, MRI is not an option.

#### 1.4.1. Assessment of vascular structures with cMRI

1.4.1.1. Pulmonary arteries. cMRI provides excellent visualization of the right ventricular outflow tract, main pulmonary artery, pulmonary

bifurcation, and branch pulmonary artery anatomy with functional information obtained with PC-MRI [7]. This includes assessment of palliated single ventricle patients with Fontan and superior cavopulmonary anastomotic connections. cMRI allows for measurement of quantitative flow in the pulmonary arteries noninvasively [16]. In patients with pulmonary blood flow dependent on aorto-pulmonary collaterals, MRA can be useful in defining all sources of pulmonary blood flow [17,18]. With our ever growing adult congenital heart disease population, repaired transposition of great arteries post arterial switch (Fig. 3C) [19], right ventricle to pulmonary artery (RV-PA) conduits (Fig. 3D) as part of the Ross [20], Yasui or Rastelli procedure, and transannular or non-transannular repair in Tetralogy of Fallot heavily rely on CMR for assessing anatomical and functional information about the pulmonary arteries and right ventricular outflow tract [4,20]. cMRI allows for definition of the geometry needed to determine suitability for transcatheter pulmonary valve implantation [21].

1.4.1.2. Pulmonary veins. cMRI is quite helpful in assessing for anomalous pulmonary venous connections (Fig. 4A) and shunt quantification in these situations [22,23]. While MRA can help visualize the pulmonary venous anatomy, cine stacks along the long axis help determine any dynamic external compression that can be seen in pseudo-stenosis of the left lower pulmonary vein



Fig. 4. 4 A. 3D MRA reconstruction of partial anomalous left pulmonary veins (PV) to innominate vein via vertical vein (VV) B. Ascending aortic dilation and aortic regurgitation

1.4.1.3. Aorta. Although CTA may offer superior imaging of the arch and head and neck vessels, cMRI offers the advantage of serially monitoring aortic root dilation and mechanism of regurgitation in patients with bicuspid aortic valve and various forms of aortopathy without ionizing radiation exposure (Fig. 4B). It also provides information about other sites of vascular ectasia and is excellent for following patients with residual aortic disease following repair of aortic coarctation [20].

1.4.1.4. Coronaries. Though coronary anatomy following surgery or Kawasaki disease is better delineated by CT or catheterization, CMR does provide important information about function, perfusion, and viability in all segments of the myocardium. With newer 3D SSFP sequences, coronary artery origin and proximal course can often be reliably identified using cMRI.

#### 1.4.2. Assessment of atria and ventricles with cMRI

1.4.2.1. Atria. Atrial level shunts and baffle leaks in patients following atrial redirection surgery can be visualized [20]. Shunt quantification can also easily be performed determining need for closure of an atrial septal defect. Anatomical definition of atrial appendages, systemic venous connections, and pulmonary venous connections is part of routine anatomic imaging in cMRI.

1.4.2.2. Ventricles. Cine SSFP imaging is critical in assessment of both biventricular and univentricular hearts. Assessing ventricular volumes and ejection fraction is part of most MRI studies and can be combined with phase contrast data to determine atrioventricular valve regurgitant fraction. Short axis images in particular allow for not just volumetric assessment but evaluation of the myocardium in patients with cardiomyopathy [24,25]. For example, in patients with ventricular non-compaction, the ratio of non-compacted myocardium to compacted myocardium is used for diagnosis [24]. In patients with Ebstenoid malformation of the tricuspid valve, cMRI is critical for assessment of the functional right ventricle. Lesions that cause increased left ventricular afterload such as systemic hypertension or coarctation can be easily assessed with cMRI as can the impact of volume loading conditions such as aortic and mitral regurgitation [26].

A frequent use of cMRI is for the assessment of patients with repaired tetralogy of Fallot (TOF). Longitudinal assessment of biventricular function, ventricular volumes, degree of pulmonary regurgitation, branch pulmonary artery anatomy, and branch pulmonary artery blood flow distribution is served by cMRI. MRI derived parameters like right ventricular function and mass are independent predictors for outcomes following pulmonary valve replacement [27].

There are excellent applications of cMRI beyond TOF. In Ebstein's anomaly, MRI derived volumetric indices like the total right ventricular volume/total left ventricular volume index correlates well with markers of heart failure [28]. In unbalanced atrio-ventricular (AV) canal defects, MRI has been useful in quantifying the smaller ventricular volume to determine suitability for biventricular conversion [29]. In unbalanced, right ventricle (RV) dominant AV canals, a minimum left ventricular end-diastolic volume (LV EDV) of 22 mL/m<sup>2</sup> and left ventricle (LV) to right ventricle (RV) stroke volume ratio of 0.19 as reported by Banka et al. allowed for biventricular conversion [30].

MRI is also useful in the diagnosis of acute myocarditis. Based on the Lake Louise criteria, cMRI assesses for hyperemia, edema, and myocardial fibrosis. The LGE pattern in myocarditis is subepicardial and patchy favoring the mid basal and infero-lateral walls [31]. Assessment for LGE is also relevant in the following lesions: transposition of the great arteries following coronary transfer [32], TOF post ventricular septal defect (VSD) repair & patch reconstruction of the right ventricular outflow tract (RVOT) [33], and in patients with Ebstein anomaly who are known to have concomitant left ventricular noncompaction [34]. Determining scar burden is particularly important in patients with HCM as this directly links with the risk of ventricular tachycardia (VT) and sudden cardiac death [35].

# 1.4.3. Assessment of the ratio of pulmonary to systemic circulation (QP:QS) and shunt fraction

PC MRI allows for non-invasive determination of QP:Qs, regurgitation fractions, and collateral volumes [36,37]. Collateral burden in patients with bidirectional Glenn or Fontan physiology can be determined as can flow characteristics of the branch pulmonary arteries in Fontan and Glenn pathways [37,38]. Aortic regurgitation severity, as indicated by holodiastolic flow reversal in the descending aorta by PC-MRI positively correlates with increased N terminal Brain Natriuretic Peptide (NT-ProBNP) [39].

#### 1.4.4. Cardiac tumor characterization

Though never approaching the sensitivity and specificity of a biopsy, cMRI serves an important role in assessment of cardiac tumors. Apart from describing the size and location of the tumor, the effect of the mass and infiltration into surrounding tissue must be noted. Benign tumors compose the bulk in children with rhabdomyoma being the most common [40]. Sequences like cine SSFP in an axial and oblique

imaging plane through the tumor, T1 weighting with and without contrast, T2 weighting, first pass perfusion, and LGE imaging together help rule out certain masses and inform a differential diagnosis [7,41].

#### 1.5. Anesthesia and cMRI

Minimizing motion artifact is critical, often requiring periods of breath holding. Multiple factors including medical history, age, comorbid conditions like developmental delay, associated hemodynamic instability, and patient cooperation play a role in choosing a sedated vs a non-sedated study [4]. Sedation alone without ensuring airway protection can lead to untoward effects like aspiration. Thus, many centers prefer anesthesia with mechanical ventilation and endotracheal intubation by a specialized cardiac anesthetic team. Respiratory artifacts can be eliminated by holding respiration for brief periods when combined with neuromuscular blockade. In infants less than six months old, the feed, swaddle and sleep technique [42], targeting the area of interest specifically, can avoid sedation and anesthesia albeit not decreasing respiratory motion artifact.

#### 1.6. Gadolinium and safety concerns specific to cMRI

Gadolinium is a rare earth material that is able to alter the relaxivity of neighboring water molecules when it interacts with its unpaired electrons. Gadolinium based contrast agents (GBCA) consist of chelating ligands that are either linear or macrocyclic, with the latter being more stable and less prone to dissociation [43,44]. Gadolinium deposits have been found in the bones and skin [45]. Linear agents have been associated with the rare development of nephrogenic systemic fibrosis [4].

Gadolinium deposits have been detected in the basal ganglia especially the dentate nucleus [46]. Neuronal deposition is cumulative with repeated contrast administration, independent of renal or hepatobiliary function [47]. Linear ionic chelates had the maximum risk of dissociation and hence deposition [48]. Therefore while choosing a contrast agent, macrocyclics are preferred [49]. Gadolinium deposition and possible long term side effects remain a clinical question for which further international collaborative studies are required [50].

Other safety concerns include provision of adequate noise protection and maintenance of optimal temperature avoiding hypothermia as children can lose large amounts of heat owing to their body surface area. Prior to the start of any scan, an extensive review of medical history including allergies to medications must be undertaken. A good ECG signal is extremely important not only for monitoring vital signs but to also allow for proper gating.

#### 1.7. Emerging technology in cMRI

The importance of precision medicine is being increasingly recognized in the field of cardiology. Use of computational models will provide low risk, quantitative data free from subjective assessments at a more personalized level [51]. Computational models using LGE proven myocarditis have been used to non-invasively predict risk of developing ventricular arrhythmia [52]. Similarly, computational modeling was performed on LGE MRI scans of adults with repaired TOF to predict the risk for development of ventricular arrhythmia which is linked to sudden cardiac death in this population [53].

Strain is the deformation produced by the application of force. Myocardial strain represents percent change in myocardial length from relaxed to the contractile state. Strain offers additional advantage over ejection fraction as it enables us to study the different spatial components of contractile function both globally and regionally [54]. Strain was able to detect subclinical myocardial dysfunction despite preserved ejection fraction [55]. Abnormal left ventricular longitudinal strain is associated with worsened exercise capacity in patients with hypertrophic cardiomyopathy despite normal systolic function [56].

Extending this concept to the left atrium, studies have demonstrated a decrease in reservoir strain in patients with hypertrophic cardiomyopathy and heart failure as an independent predictor of adverse events [57]. Right atrial feature tracking in patients with Ebstein's anomaly detected a decrease in atrial reservoir and booster pump function, correlating well with clinical indices of heart failure like B-type Brain Natriuretic Peptide (BNP) and New York Heart Association (NYHA) classification [58]. Feature tracking in cardiac MRI is a two-dimensional (2D) imaging technique that can be performed on standard CMR cine SSFP sequences on several commercial software platforms. It has been used in congenital heart disease to show improvement in left ventricular strain post pulmonary valve replacement in patients with repaired TOF [59], to demonstrate persistence of abnormal global longitudinal strain despite preserved ejection fraction in patients with coarctation of the aorta [60] and in Fontan patients with decreased exercise tolerance. Strain parameters are abnormal in patients with isolated bicuspid aortic valve and in patients with acute or prior myocarditis with preserved ejection fraction regardless of the presence of LGE [61,62].

Parametric mapping is based on relaxation properties of the myocardium that allows for multiple images of the same region of interest in the myocardium to be acquired with different sensitivities to the parameter of interest. The various signal intensities thus obtained are fit in a pixel wise fashion to a parametric map thus providing a more quantitative rather than qualitative way of assessing changes in the myocardium. Parametric mapping has the advantage of being used to monitor response to chelation therapy as in thalassemia and is considered the gold standard for doing so [63]. In myocarditis, myocardial inflammation results in abnormal parametric mapping results. These have been included in the most updated form of the Lake-Louise criteria [31].

Artificial intelligence is an emerging field in medical imaging and incorporates concepts such as machine learning and advanced neural networks. It is increasingly applied in cardiac clinical diagnostics to facilitate fully-automatic and accurate segmentation of cardiac structures with chamber quantification and ejection fraction assessment [64,65]. Tissue characterization using neural networks has been used to quantify left ventricular scar volumes in patients with hypertrophic cardiomyopathy [66,67].

Four-dimensional flow imaging, or (4D-flow), is analogous to PC-MRI but involves velocity encoding in all three spatial dimensions throughout the cardiac cycle thus providing a time resolved 3D velocity feature [68]. In congenital heart disease, it has gained popularity in Fontan patients by determining the visual and quantitative differential pulmonary blood flow, uneven mixing pattern of the hepatic factor rich venous blood, shunt calculation, and superior vena cava (SVC) flow patterns [69]. In repaired TOF patients there is marked variation in flow characteristics, vortex formation in the pulmonary trunk and its branches as well as branch pulmonary artery flow with evidence of increased wall sheer stress [70]. 4D flow is a viable tool for assessing abnormal flow dynamics in patients post repair of coarctation of aorta [71]. In patients with bicuspid aortic valve, 4D flow was able to determine a higher altered wall stress due to impingement of high velocity flow jets [72].

#### 1.8. Contraindications

True contraindications for cMRI are becoming rare as centers become more comfortable in scanning patients with pacemakers and defibrillators. A rigorous screening safety protocol needs to be in place and ideally performed well before the patient arrives for the scan. Relative contraindications for cMRI are often center specific.

#### 2. Cardiac computed tomography (cardiac CT)

#### 2.1. Introduction

Modern CT technology has greatly expanded applications in pediatric and congenital heart disease. Cardiac CT scan provides excellent spatial and temporal resolution allowing for visualization of cardiac structures in small children with high heart rates [73]. Post processing techniques and radiation reduction techniques have reduced the historically limiting radiation dosage while preserving image quality [73,74].

#### 2.2. Scan/technical basics

Based on the area covered by the scanner with every rotation, CT scanners are often referred to by the number of slices per rotation (e.g. 256 slice or 64 slice). As temporal resolution is the time taken to produce one image, a higher number of slices covered per rotation results in improved resolution. Data acquired by prospective or retrospective ECG triggered sequences is reconstructed by partial scan reconstruction or multiple segment reconstruction [75]. Partial scan reconstruction is the minimum amount of data required to construct an image by rotating the tube by 180°, usually done over a single cardiac cycle [75,76]. Using faster scanners with rotation times of 300 ms, the temporal resolution is further decreased to 170-180 ms. To achieve even better temporal resolution, in addition to having higher gantry rotation time, there has been the push for dual source CT scanners or even multisource CT scanners. In dual source CT scanners, as image is reconstructed from two sources 90° apart, the temporal resolution for a gantry rotation can be as low as 80 ms.

Pitch is defined as the ratio of the table increment per gantry rotation. Values less than one imply overlapping of x-ray beam and high patient doses. Cardiac CT usually requires values less than one to minimize motion artifacts and gaps in images at the expense of increased radiation [75]. Pitch is dependent on the heart rate and controls spatial resolution. The lowest possible tube current expressed in milliampere (mA) for a given tube potential expressed in kilovolts (kV) should be used. Automatic tube current modulation impacts mA based on scout images. In small children typical ranges are from 70 kV to 80 kV [77].

There are two basic types of ECG triggering for cardiac CT. Retrospectively gated spiral scanning, in which the x-ray beam is continuously on and the patient is moved through the gantry at a slow speed to achieve the ideal low pitch, is uncommonly used in the pediatric population and reserved when functional analysis by CT is needed. It results in higher radiation exposure than prospective gating. Prospectively gated high pitch sequences, also called step-and-shoot acquisition, offers far less radiation exposure due to narrow acquisition window. This is especially useful when a single cardiac phase is of interest. Prospective ECG triggered flash is a very fast spiral scan mode where the image obtained can fit into one cardiac cycle provided the heart rate is low.

Image acquisition is also determined by automatic or manual bolus tracking. Automatic bolus tracking triggers a scan when contrast gets to a pre-defined density, Hounsfield unit (HU), in a region of interest placed in the structure of interest. Manual bolus tracking is used in children with complex systemic anatomy, intracardiac mixing and systemic venous anomalies where it is difficult to predict the timing of contrast. The scan is initiated when the structure of interest is identified visually on the monitoring sequences.

For a given voltage, contrast enhancement increases proportionally with iodine concentration. Contrast administration requires particular attention. The peripheral IV location, contrast and injection protocol are critical and generally based on the anatomy and clinical question. Commonly used injection protocols include:

- A. Biphasic protocol (contrast at a constant rate followed by a saline flush) for systemic or pulmonary angiography with acquisition timed to opacification of the region of interest (ROI).
- B. Biventricular or triphasic protocol (two phase contrast with first contrast phase at a higher rate followed by the second contrast injection, followed by saline flush) allows for simultaneous visualization of both pulmonary and aortic structures in lesions such as repaired TOF or Ross procedure.
- C. Venous two-phase protocol (30-50% of total contrast administered followed by a 30-60 second pause followed by a biphasic protocol. The second phase contrast injection (during the biphasic protocol) is tailored to optimal opacification of the primary anatomy of interest.) This is used for single ventricle physiology patients.
- D. Single phase contrast injection is commonly used in practice in which a contrast bolus (typically 1–2 ml/kg) is administered until standard adult dosages are achieved. By mixing saline, the injection time lengthens, maximizing the probability of optimum enhancement at the time of image acquisition in young patients with very short image acquisition times or variable contrast transit times.

#### 2.3. Safety concerns/radiation effects

CT depends on ionizing radiation for image formation. Although typically low-level, DNA damage has been shown to occur with ionizing radiation. Greater sensitivity of growing tissue to ionizing radiation, increased value and use of this modality in the youngest of children, and longer anticipated lifetime make children a particularly vulnerable group [78]. Due to smaller size, when compared with larger children, an identical degree of exposure results in greater dosage to tissues due to their size. Various international expert regulatory bodies are still uncertain about the risk associated with low dose ionizing radiation, with an observation of a linear relationship between dose and risk based on available data. The principle of "as low as is reasonably achievable" (ALARA) highlights the importance of justifying an appropriate indication to perform the study and optimizing imaging parameters to use only the required amount of radiation to answer the clinical question. In pediatric congenital heart disease, the Image Gently Have-A-Heart Campaign is promoting the appropriate use of medical imaging studies while minimizing radiation exposure [79].

Measured in Sievert (Sv), effective dose (ED) reflects the relative risk of detrimental biological effects from exposure to ionizing radiation. As a whole body metric, ED can be used to compare the ionizing radiation exposure across all imaging modalities. ED increases with age. Prospective ECG triggered examinations have lower ED (0.05 to 5.8 mSv) than retrospectively gated ECG exams (0.5 to 28 mSv) [79].

#### 2.4. Patient preparation, anesthesia and sedation considerations

Renal function assessment, pregnancy testing and contraindications to administering beta blockers for heart rate control must be reviewed prior to scanning. Beta blockers help lower heart rate and reduce heart rate variability, thus reducing motion artifacts while allowing for utilization of radiation reduction algorithms. For detailed coronary imaging including ostial anatomy and functional imaging, breath holding is required to eliminate respiratory motion which may require sedation dependent on patient age. When only proximal coronaries are to be imaged, sedation is usually not required. Image quality can be improved using prospectively triggered high pitch or volumetric scan mode. For anatomy scans, a free breathing technique can be performed. Infants less than 6 months can be swaddled while children between 6 months and 4 years may require sedation to prevent movement in the scanner [79].

#### 2.5. Common indications

A. Coronaries: Cardiac CT has shown particular utility in assessment

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Fig. 5. 5 A and B: CT reconstructed images depicting coronary artery to pulmonary artery fistula in pulmonary atresia/ventricular septal defect C. Right coronary artery (RCA) aneurysm in Kawasaki disease D. Double aortic arch with simultaneous visualization of the airway

of coronary arteries. Congenital coronary abnormalities including slit like ostia, anomalous aortic origin which can be important etiologies for sudden death in athletes, coronary fistula (Fig. 5A and B), congenital heart disease post-surgical coronary manipulation and Kawasaki (Fig. 5C) benefit from CT [80–82].

- B. Vascular structures: CT scan is often the diagnostic modality of choice for detecting vascular rings, arch anomalies, and slings. It can also enable concurrent visualization of the airway (Fig. 5D). It is also helpful for detection of pulmonary venous anomalies especially sites of obstruction and anomalous pulmonary venous return. Abnormalities of the aortic arch, ductal dependent lesions, aortopulmonary window, and branch pulmonary artery abnormalities can easily be evaluated with CT [83]. CT is preferred to MRI in the definition of a patent ductus arteriosus.
- C. Single ventricle physiology: CT helps determining complex anatomy consisting of anomalous pulmonary venous anatomy prior to Stage 1 palliation. Post initial palliation, CT is useful for evaluation of shunt thrombosis, coronary anatomy, and conduit narrowing. CT, along with cMRI, is being used in some centers in place of catheterization prior to proceeding with the next stage of palliation. In patients with a superior cavopulmonary anastomosis or Fontan, particular attention is needed during contrast administration and image acquisition.
- D. Function: Though not used frequently because of increased radiation exposure relative to cMRI, CT can be used for volumetric ventricular assessment similar to cMRI. With retrospective gating, as there is continuous radiation exposure, ECG based tube current modulation ensures full radiation only during a specified portion of the cardiac cycle while tube current is reduced for the remainder of the cycle [81]. In prospective ECG gated imaging, the data acquisition window occurs only during end-systole and end-diastole. Studies have shown interchangeable results in function assessment while comparing MRI vs CT [84].

#### 2.6. Emerging technology/future

#### 2.6.1. Iterative techniques

Advanced non-linear iterative reconstruction algorithms are now being utilized by vendors to decrease the noise and improve contrast resolution at lower doses. They are based on the principle of modeling where expected data sets generated are compared to the actual acquired dataset. This is especially useful in pediatric patients in whom we try to achieve a comprehensive scan using the lowest radiation dose as possible [85,86].

#### 3. Advantages of CT over MRI for specific clinical scenarios

CT is the gold standard for visualization of smaller caliber vessels seen in pediatrics and more distal coronary vasculature. It is also superior for detailed assessment of the proximal segments including presence of anomalous origin or course of the coronary artery, presence of stenosis, intramural component, slit like orifice or an intra myocardial course [87,88]. Palliated congenital heart defects involving translocation of coronary buttons as in arterial switch operation or Ross procedure and acquired coronary pathology in Kawasaki disease greatly benefit from CT scans [81,89].

Due to short scan times, CT can be successfully performed without sedation in children and young children making this favorable over cardiac MRI. By offering ultrafast times for image acquisition, CT gives rapid diagnostic information in clinically fragile patients, single ventricle patients, critically ill patients, neonates, Williams syndrome, or patients with severe outflow tract obstruction [79]. Patients with pacemakers, cochlear implants, defibrillators, or intrathoracic metal in whom cMRI is contraindicated are also served well by cardiac CT.

#### 4. Appropriate use criteria (AUC) for cardiac CT and MRI

In a joint effort by the American College of Cardiology (ACC)/ American Heart Association (AHA)/American Society of Echocardiography (ASE)/Heart Rhythm Society (HRS)/International Society for Adult Congenital Heart Disease (ISACHD)/Society for Cardiovascular Angiography and Intervention (SCAI)/Society of Cardiovascular Computed Tomography (SCCT)/Society for Cardiovascular Magnetic Resonance (SCMR)/Society of Pediatric Echocardiography (SOPE) 2020, AUC criteria for preferring MRI over routine transthoracic echocardiogram (TTE) included conditions involving the right ventricle (TOF, Ebstein's anomaly) owing to its complex shape and retrosternal position. Higher costs and need for sedation limit its use in children who are asymptomatic or with mild disease in whom a TTE is preferable. Tissue characterization, measurement of blood flow with calculation of both ventricular function and volume, in the absence of radiation exposure, make MRI superior to traditional CT. In patients with complex vascular anatomy or assessing coronaries as described above, CT is superior. It also useful in pre-procedural planning in adults with congenital heart disease or in patients with a clinical change such as occurrence of new ischemic symptoms post arterial switch operation [[90]]. There are also standard reporting guidelines for cardiac MRI and CT, with special focus on congenital heart disease [[91]]. A comparison of various available modalities used in congenital heart disease is described in Table 1).

#### 5. Conclusions

Overall, both CT and MRI are integral imaging modalities for patients with congenital and acquired heart disease. It is imperative to realize that each of the modalities supplements each other based on their individual strengths. They both are useful tools in the daily practice of pediatric cardiology.

#### **CRediT** author statement

Rao, S: Conceptualization, methodology, validation, writing - original draft.

Madueme, P: resources, validation, writing - review and editing. Podberesky, D: resources, validation, writing - review and editing. Cartoski, MJ: Conceptualization, methodology, validation, writingreview and editing, resources, supervision.

#### Declaration of competing interest

Rao, S: No conflicts of interest to disclose.

	Great vessels	Pulmonary veins	AV valves/semilunar valves	Ventricular function	Coronaries	Complex CHD	Tissue characterization	Shunt
MRI	4	4 (anatomy+ flow)	2/3 (regurgitation)	4	3	4 (anatomy + flow)	4	4
CL	4	°.	1/2 5 5	1 (ECG gated)	4	°,	2	No
Echocardiography	ŝ	ŝ	4	e n	2 (proximal only)	ε	2	2
Catheterization	4	4 (wedge pressure)	2/2 (pressure gradients)	3 (end diastolic pressure)	4 (gold standard)	3 (PA pressures)	1	4
not used commonl	v with major limita	tions; 2 can be used but	has significant limitations with	availability of better alternat	ive imaging; 3 commo	nly used but may have li	mitations; 4 test of choice.	AV valves

Table .

Comparison of different imaging modalities used in congenital heart disease

Atrioventricular valves, ECG Electrocardiogram, PA pulmonary artery

Madueme, P: No conflicts of interest to disclose. Podberesky, D: No conflicts of interest to disclose. Cartoski, MJ: No conflicts of interest to disclose.

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