

CONGENITAL HEART DISEASE

Technical Aspects of Pediatric CMR

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ABSTRACT

Cardiac magnetic resonance (CMR) of the pediatric patient involves a unique set of technical challenges above and beyond those encountered in adult imaging. Anatomical structures are smaller, demanding greater spatial resolution; heart rates are high, demanding greater temporal resolution; and patients maybe sedated or uncooperative, rendering breath-hold imaging strategies useless. Despite these difficulties, CMR offers several advantages over other imaging modalities, including soft tissue contrast, lack of ionizing radiation, a capacity for true three-dimensional imaging, accurate flow quantification, and freely selectable imaging planes. These advantages and continued advances in MR hardware, software, and imaging techniques are bringing CMR into more widespread use in pediatric cardiology.

This review is a summary of the primary techniques used in pediatric CMR for both congenital and acquired cardiovascular disease. The fundamentals of CMR pulse sequences and physiological synchronization of data acquisition are described, and imaging applications are reviewed. While the basic imaging sequences and techniques are common to both pediatric and adult CMR, some significant differences in imaging priorities and strategies are discussed.

INTRODUCTION

Cardiac magnetic resonance (CMR) of the pediatric patient involves a unique set of technical challenges above and beyond those encountered in adult imaging. Anatomical structures are smaller, demanding greater spatial resolution; heart rates are high, demanding higher temporal resolution; and patients may be sedated or uncooperative, rendering breath-hold imaging strategies useless. Despite these difficulties, CMR offers several advantages over other imaging modalities, including soft tissue contrast, lack of ionizing radiation, a capacity for true threedimensional imaging, accurate flow quantification, and freely

Received 2 August 2005; accepted 19 February 2006. Keywords: Magnetic Resonance Imaging, Pediatric, Congenital Heart Disease, Cardiac Magnetic Resonance. Correspondence to: Orlando P. Simonetti, PhD The Ohio State University 473 West 12th Avenue, Room 110 DHLRI Colombus, OH, 43210-1252 fax: 614-247-7799 e-mail: orlando.simonetti@osumc.edu selectable imaging planes. These advantages and continued advances in MR hardware, software, and imaging techniques are bringing CMR into more widespread use in pediatric cardiology.

This review is a summary of the primary techniques used in pediatric CMR for both congenital and acquired cardiovascular disease. While the basic imaging sequences and techniques are common to pediatric and adult CMR, there are some significant differences in imaging priorities and strategies that will be pointed out and discussed.

The first section deals with some of the fundamental aspects of CMR pulse sequences and image acquisition strategies. The second section covers the various pulse sequences in the functional imaging categories of localization, morphology, cardiac function, velocity quantification, first-pass perfusion, and delayed-enhancement. In the final section, some future directions for technical advancement are discussed.

PULSE SEQUENCE FUNDAMENTALS

Spin echo

ECG-gated spin echo (SE) imaging has been used for depiction of cardiovascular anatomy for over 20 years (1). A 90°

RF excitation pulse is followed by a 180° refocusing pulse to form a spin echo. Wash-out of spins during the time between excitation and refocusing reduces blood signal and provides high contrast between lumen and vessel wall, or cardiac chambers and myocardium (2). However, scan times are long, and images may suffer from respiratory motion artifacts and incomplete suppression of blood signal. Turbo (TSE) or fast spin echo applies multiple 180° pulses to form multiple echoes following each excitation pulse, increasing the efficiency of image acquisition. TSE techniques combined with blood-nulling pre-pulses are used in cardiovascular imaging as a means to reduce acquisition time to a breath-hold and provide more reliable blood signal suppression (3). TSE can be extended to single-shot imaging (RARE or HASTE) by sampling enough echoes after a single excitation to reconstruct an entire image (4, 5). However, compared to SE or TSE, single-shot imaging has relatively poor spatial and temporal resolution and may not be useful at the high heart rates of infants and young children. The parallel acquisition techniques of SMASH (6), SENSE (7), and GRAPPA (8) can reduce scan time by deriving spatial encoding information from multielement coil arrays. These techniques have improved single-shot imaging by reducing the shot-time, improving temporal resolution and reducing motional blurring. The three basic forms of cardiac-gated spin echo sequences (SE, TSE, and HASTE) are shown in Fig. 1. Spin echo based black-blood techniques are no longer commonly used for basic anatomical imaging having been supplanted by rapid, bright-blood single-shot and 3D SSFP as well as contrast-enhanced 3D MR angiography. However, SE type sequences are still commonly used for T2-weighted imaging and tissue characterization.

Spoiled gradient echo (GRE)

The spoiled gradient echo pulse sequence forms the basis of a wide variety of cardiac imaging applications, including cine, velocity mapping, first-pass perfusion, delayed-enhancement viability imaging, and contrast-enhanced angiography. All of these applications are built on the same basic gradient echo building block using a short echo time (TE), short repetition time (TR) and low flip angle excitation with gradient and/or RF spoiling of transverse magnetization following each readout. Multiple variations have been created, tailored to specific imaging applications, through the use of velocity encoding and compensation, magnetization preparation pulses, and 2D and 3D acquisition strategies.

Gradient echo cine imaging relies on inflow enhancement to generate high signal in blood flowing through the plane of the image (9). Today, most cine imaging applications are based on the trueFISP or SSFP (steady-state free precession) sequence (10, 11, 12), however, spoiled gradient echo cine continues to play a role in cine imaging of valves and vascular stenoses. Rapid flow through valves causes signal enhancement in GRE cine, as shown in Fig. 2, facilitating planimetry of the valve orifice. The flow disturbances caused by valve stenosis or insufficiency are often more easily visualized using GRE than with SSFP. Flow disturbances typically result in controlled dephasing of the signal



Figure 1. Comparison of standard gated spin echo (A) to segmented turbo spin echo (B) to single-shot HASTE (C). The three cardiac synchronized acquisition strategies diagrammed in the figure for spin echo based sequences can be generalized to the other basic sequence types of spoiled gradient echo and steady-state free precession.





in GRE while these disturbances can produce variable results in SSFP images.

Phase velocity mapping (13, 14) is another important application of GRE in pediatric CMR. The motion of blood or tissue during the application of imaging gradients results in a phase shift relative to stationary tissue. In order to separate this phase shift due to velocity from other sources of phase shift, such as local field inhomogeneities and chemical shift, a reference data set is acquired (15). In the reference data acquisition, the gradient pulses are designed to eliminate any phase due to constant velocity by the technique of velocity compensation or gradient moment nulling. A second set of image data is acquired in which a phase shift is generated proportional to magnitude and direction of velocity. This is accomplished through the use of flow encoding gradient pulses embedded within the conventional gradient echo cine pulse sequence. After subtracting the phase due to other sources, the remaining phase difference between the velocity encoded and velocity compensated datasets is proportional to velocity. A "phase image" is reconstructed in which the signal intensity is proportional to the magnitude of the velocity, and the sign of the signal (positive or negative) indicates direction. An example is shown in Fig. 3.

Since velocity mapping requires acquisition of twice as much data (flow encoded and flow compensated), scan times tend to be longer than conventional cine imaging. Recently, parallel imaging techniques have been combined with velocity mapping to accelerate data acquisition. This technique has been used for left-to-right shunt quantification in pediatric patients (16). Parallel imaging has also been combined with a multi-echo readout for real-time velocity mapping (17). Besides providing a shorter scan time, real-time flow techniques are insensitive to respiratory motion and arrhythmia. While real-time imaging involves some sacrifice of spatial and temporal resolution over conventional, segmented acquisitions, initial clinical results in pediatric patients are promising (18).



Figure 3. In this patient with bicuspid aortic valve, two sets of images are reconstructed from the velocity mapping cine sequence. The magnitude image shown in (A), used for anatomic orientation is equivalent to a bright-blood GRE cine image. In the phase-velocity image shown in (B), pixel intensity is proportional to through-plane velocity. Medium gray corresponds to zero velocity, while bright (+) and dark (-) signal indicate flow direction.

The other important applications of GRE sequences in pediatric CMR are first-pass perfusion, delayed enhancement, and contrast-enhanced MRA. All of these rely on the inherent T1 sensitivity of GRE, the ability to enhance T1-weighting by means of magnetization preparation pulses, and the T1-shortening effect of Gadolinium based contrast agents. These techniques are discussed in more detail in the sections on those specific applications.

Steady-state free precession (SSFP)

The technique of steady-state free precession (SSFP) or true-FISP has been responsible in part for the rapid advancement of CMR over the past five years. SSFP relies on very short repetition times (TR) for insensitivity to field inhomogeneity. For this reason, while the SSFP sequence has been known for some time (10), the first practical applications of SSFP in cardiac imaging (11, 12) only came with the introduction of fast gradient systems. Cine imaging is the cornerstone of any CMR exam, and SSFP provides a dramatic improvement in cine image quality, contrast, and signal-to-noise over GRE sequences. In SSFP, transverse magnetization is refocussed from one RF pulse to the next, resulting in an image contrast which is related to the ratio of T2/T1 relaxation parameters. This ratio is on the order of 3x higher in blood than in myocardium, resulting in inherently high bright-blood contrast without strong reliance on inflow enhancement. SSFP has generally replaced spoiled gradient echo sequences for cine imaging as it does not suffer from saturation and loss of signal in situations of slow or in-plane flow. SSFP imaging does have its own limitations, however. Its sensitivity to field inhomogeneity is dependent on TR. Inhomogeneities typically exist at the air-tissue interface between the lungs and heart, and near surgical clips, sternal wires, or stents, and can cause dark band artifacts if the TR is not sufficiently short. Besides cine imaging, SSFP has also had success for single-shot 2D and bright-blood 3D anatomical imaging (19). Magnetization prepulses (e.g., inversion recovery, saturation recovery, bloodnulling) can be combined with SSFP (20) to take advantage of the higher SNR efficiency than GRE in applications such as firstpass perfusion and delayed-enhancement. Of course, the goal in these applications is to detect signal intensity changes in tissue, so any dark band artifacts are of particular concern.

Physiological synchronization Basics of cardiac synchronization

CMR pulse sequences, with few exceptions, are synchronized to the cardiac cycle by means of an electrocardiogram (ECG). Data are collected at the same time relative to the ECG R-wave over multiple heartbeats in order to reconstruct an image representative of a specific phase of cardiac contraction. In cine imaging (21), multiple images are reconstructed across the cardiac cycle and viewed in a movie loop depicting the motion of the beating heart or flowing blood.

Optical fiber or even wireless electrode leads are employed to reduce ECG signal interference due to gradient field switching.

The vectorcardiogram (VCG) method (22) has been adopted as a means of improving the reliability of R-wave detection in the face of ECG signal distortion caused by blood flow in the magnetic field. Finger pulse oximetry can also be a useful alternative to the ECG signal for physiological synchronization of pulse sequences as it is an optical signal insensitive to electrical interference. However, it relies on good peripheral circulation, which is not always present in patients. The finger pulse trigger is based on peripheral blood flow and lags behind the R-wave trigger by 200 - 300 msec at normal heart-rates. This time difference must be taken into account in setting appropriate pulse sequence timing parameters.

Prospective triggering vs retrospective gating

Most imaging techniques designed to acquire images at a single temporal phase of the cardiac cycle (black-blood TSE, first-pass perfusion, delayed-enhancement, angiography) utilize prospective triggering, while most cine imaging techniques now employ retrospective gating. In prospective triggering, a series of RF and gradient pulse events with fixed timing follows each R-wave trigger. For example, a single-shot 2D SSFP image may be acquired, timed to fall in diastole to avoid most systolic motion. Once the MR data acquisition events are completed for a given heartbeat, the system halts and waits for the next Rwave to arrive, triggering the next series of events in the pulse sequence. This required waiting period associated with prospective triggering causes it to miss a portion of the cardiac cycle at end-diastole. If the heart-rate is irregular and the next R-wave occurs before the system is ready to detect it, entire heart beats will be skipped.

Retrospective gating techniques acquire data continuously from one R-wave trigger to the next. Data acquisition does not halt and wait for the next trigger. Instead, the MR system monitors the ECG waveform during data acquisition and switches to the next phase encoding steps as soon as a trigger is detected. After the acquisition is completed, the data are sorted based on their relative position within the cardiac cycle, and a cine loop representing an entire R–R interval is reconstructed. While an arbitrary number of frames may be reconstructed by interpolation of data, the true temporal resolution is still defined by the acquisition parameters.

Respiratory gating

While rapid imaging techniques have enabled most CMR scans to be reduced to a reasonable breath-hold period, pediatric patients are often sedated or too young to cooperate with breath-hold instructions. In sedated infants and small children, breathing is often shallow and regular, and it is generally sufficient to acquire multiple signal averages to "average out" respiratory motion artifact. This simple approach also inherently improves image signal-to-noise, but averaging in the presence of significant motion can result in blurring and loss of spatial resolution. Alternatively, respiratory gating strategies have been employed to synchronize data acquisition to the respiratory cycle and/or prospectively adjust slice position to compensate for motion. Respiratory bellows have been used to detect and synchronize the acquisition to respiratory motion, but with inconsistent results. More recently, navigator echo respiratory gating (23) techniques have been developed to accurately and reproducibly monitor and correct for respiratory motion of the heart. The navigator echo method uses an MR signal to detect and monitor diaphragm position during image acquisition. The heart is assumed to move in proportion to diaphragm motion, and both gating (rejection of data collected during active phases of respiratory motion) and prospective slice correction can be applied based on this measurement of motion. The primary application for navigator gating has been three-dimensional coronary MRA, which has some utility in pediatric CMR in diagnosis of Kawasaki disease (24) and anomalous coronary arteries (25). More recently, navigator gated SSFP sequences have been used for high resolution three-dimensional angiography of the great vessels in adolescent and adult congenital heart disease (19).

Data acquisition strategies

Concept of segmentation

Three basic modes of ECG-synchronized data acquisition can be defined, as outlined above for spin-echo based sequences and diagrammed in Fig. 1. In the standard method of cardiac gating or triggering, e.g., SE imaging, a single line of data for each image is acquired each cardiac cycle. While this method affords the highest possible temporal resolution as defined by the time to sample only one line, it also results in the longest scan time. This form of gating, while rarely used in adult imaging, is still important in CMR of infants and small children with extremely high heart rates. A more commonly used cardiac synchronized acquisition strategy is k-space segmentation (26). In a segmented acquisition, such as the TSE sequence shown in Fig. 1, several lines (typically from 3 to 64) are acquired each cardiac cycle. While temporal resolution is sacrificed, the image acquisition time is reduced by the segmentation factor, making rapid breathhold imaging possible. In pediatric imaging, breath-holding is only appropriate for children old enough to cooperate with the operator. Segmented acquisition may also be combined with averaging or respiratory gating methods for imaging during free breathing.

Single-shot and real-time imaging

The concept of segmentation, i.e., sampling more than one line of data per cardiac cycle, can be extended to the extreme of sampling all lines inside of a single heartbeat. This approach is termed "real-time" when in reference to cine imaging or "singleshot" when pertaining to static imaging. Real-time does not necessarily imply that the images are reconstructed and displayed in real-time. Rather, it implies that these cine images are acquired as a series of complete images acquired rapidly and sequentially in time depicting actual heartbeats (27). This differs from standard or segmented acquisition techniques which build up a cine loop representing a composite cardiac cycle reconstructed from data acquired over a number of heartbeats. Single-shot refers to the acquisition of all image data in a "single shot," rather than segmented over a number of beats. In these cases, the requirement of sampling an entire image, or even multiple images worth of data inside of a single heartbeat, demand compromises in spatial and temporal resolution compared to segmented acquisitions. However, single-shot and real-time imaging offer distinct advantages over segmented acquisitions and are becoming more widely used as temporal and spatial resolution are improved. Cardiac arrhythmias, for example, can destroy the quality of segmented gated acquisitions due the discrepancies in data collected in different heartbeats. Real-time imaging, on the other hand, doesn't combine data from multiple beats and is therefore much less sensitive to variations in rhythm. Likewise, single-shot image acquisition is fast enough to "freeze" respiratory motion and is insensitive to breathing artifacts. Insensitivity to arrhythmia and breathing motion make single shot imaging the only viable option in some patients. The advent of these rapid techniques has meant that even the sickest, most uncooperative patient can be successfully imaged. However, given the spatial and temporal resolution compromises necessary to achieve the speed of real-time imaging, these techniques have seen only limited application in pediatric CMR. As the technology advances and spatial and temporal resolution are improved, real-time and single-shot imaging will take on a more important role in pediatric imaging. Even using today's MRI technology, real-time fetal cardiac MRI has been demonstrated (28), despite the extreme demands on temporal and spatial resolution of this application.

Data sharing

Techniques for sharing raw data between frames in a time series of images have been developed to improve the effective frame rate (29, 30). Image frames can be reconstructed closer together in time by overlapping the raw data from one image to the next. While true temporal resolution, defined as the period of time to acquire a given image, is not improved by data-sharing, the temporal spacing between reconstructed images is improved (31). This leads to a smoother display of cardiac motion or flowing blood. Data sharing has been used effectively in prospectively triggered cine imaging, flow quantification, real-time imaging, and more recently in time resolved MR angiography (32, 33). Time resolved 3D MRA can provide additional information on the dynamics of blood flow, baffle leaks, and shunts in complex congenital heart disease (34).

Magnetization preparation

A variety of different image contrasts can be generated by the use of magnetization preparation pulses. T1-weighting can be imparted by inversion-recovery (IR) and saturation-recovery (SR) pulses. T2-weighted preparation has been successfully used to improve blood-myocardium contrast in 3D acquisitions (35). Blood-nulling is achieved through double-inversion (36). Fat suppression, grid tagging, and spatial pre-saturation are also all examples of magnetization preparation schemes used in CMR. These preparations provide the flexibility neces-



Figure 4. Short-axis images from a normal volunteer demonstrating the flexibility and image constrast varation made possible by magnetization preparation. Each of the four images shown was acquired using the same segmented SSFP readout, but each preceded by a different magnetization preparation. Upper left image (A) shows the native SSFP contrast with no magnetization preparatory pulses. Upper right image (B) is the same sequence with the addition of a T2-weighting preparation. Note the darker myocardium and skeletal muscle due to the T2-weighting. Lower left image (C) demonstrates black-blood contrast generated by the double-inversion preparation. Lower right image (D) shows the effect of a non-selective inversion recovery pulse. The inversion time was set to null myocardium, as is done in delayed enhancement imaging.

sary to successfully perform the wide variety of imaging functions necessary for cardiac imaging. Several examples showing the effect of different magnetization preparation schemes combined with a segmented trueFISP readout are shown in Fig. 4.

Coils for pediatric CMR

Small coils placed directly on the chest and under the back of a child can significantly improve SNR. In selecting appropriate coils for a pediatric CMR exam, it is also important to consider the arrangement of multiple array elements for optimal application of parallel acquisition techniques (6, 7, 8). While there are some commercially available pediatric coils, these are typically designed for imaging of the brain and spine. Imaging the heart of an infant or very small child often requires the use of adult coils designed for other applications. For example, infants may fit within a standard head coil, and flexible coils designed for orthopedic imaging can be wrapped around the chest of a small child. Alternatively, some coil arrays permit selection of only specific elements out of the total array, allowing for the use in larger children of cardiac coils designed for adults.

IMAGING APPLICATIONS

Localization

The first step in any CMR exam is to identify the appropriate scan planes needed to answer the clinical questions. This generally means taking steps to obtain images in the standard cardiac views (short-axis, vertical and horizontal long-axis) and valvular views. These views are easily achieved through the use of single-shot localizers, generally using either bright-blood SSFP or dark-blood HASTE. Either technique will generate a complete image in less than a heart-beat, and one can very quickly get to the standard cardiac views by positioning one slice off of another.

In the case of complex congenital heart disease, the standard cardiac views may no longer apply. Anatomic anomalies can make it difficult to determine appropriate views by standard slice positioning methods. In these cases, a useful alternative approach is to first obtain a 3D volume covering the entire region of interest, generally including the heart and great vessels. This data can be obtained either using a 3D SSFP sequence or by acquiring a series of overlapping 2D slices with either single-shot or segmented SSFP. Because of the large number of slices acquired, this type of scan can take several minutes. The acquisition is generally either respiratory gated, or multiple averages are obtained to suppress respiratory motion artifact. Once the 3D volume data are acquired, they can be loaded into a multi-planar reconstruction (MPR) tool to define the oblique orientations needed to image the anatomy of interest, as shown in Fig. 5. The slice orientations determined in this fashion are used as the scout images for subsequent imaging using cine, flow quantification, and other techniques.

Another approach to slice positioning gaining in popularity is real-time interactive imaging. In this method, images are acquired in rapid succession, reconstructed, and displayed in real-time. Real-time control allows the operator to steer the scan plane into the desired views, much like echocardiography. Interactive scan control is not generally commercially available but is an active area of research and development.

Cardiac and vascular anatomy

Accurate visualization of cardiac and vascular anatomy is critical to surgical planning and assessment of results in congenital heart disease. MRI can provide high resolution, high contrast, anatomical images in freely-selectable 2D planes or true 3D volume scans. Anatomical images, combined with the functional information provided by cine, velocity mapping, and dynamic contrast angiography techniques make MRI ideally suited to the evaluation of congenital heart disease patients.





Figure 5. MPR reformats in a patient with double-outlet right ventricle and coarctation of the aorta who underwent palliative repair with a lateral tunnel Fontan and subclavian flap angioplasty. MPR is useful in the single ventricle patient where conventional imaging planes are difficult to obtain such as the horizontal long axis or four-chamber (A), short axis (B) and outflow-tract (C) views. Rapid acquisition and reconstruction of scout images may decrease overall scan time in children with complex congenital anatomy.

SSFP

With the advent of fast gradient hardware, bright-blood SSFP techniques are taking over the anatomical imaging role traditionally held by gated spin echo. Single-shot, 2D SSFP images are insensitive to cardiac arrhythmia and breathing motion and provide a rapid, high resolution survey of cardiovascular anatomy. In the high heart rates often encountered in pediatric patients, kspace segmentation is employed to improve temporal resolution in 2D or 3D volumetric scans. With segmentation, breath-hold, averaging, or respiratory gating are required to suppress breathing artifact.

Black-blood sequences

While bright-blood SSFP and contrast-enhanced MRA have become more important tools for anatomical imaging, black-blood SE-based techniques still play an important role in tissue characterization in pediatric CMR. These techniques offer means of assessing pathological changes in T1 and T2 relaxation parameters in cardiac and vascular tissue. Myocarditis (37), various cardiomyopathies, pericarditis, cardiac masses, and vasculitis all can show an increase in T2. Black-blood SE-based imaging with blood suppression pulses provides



Figure 6. Black-blood SE imaging in a patient with unrepaired tetralogy of Fallot, pulmonary atresia and major aorto-pulmonary collateral arteries (MAPCAs). Black blood imaging identified not only a severely dilated ascending aorta but also numerous MAPCAs arising from the descending aorta supplying the right and left pulmonary arteries.

high-resolution T2-weighted images of cardiac and vascular tissue (38), as demonstrated in the example in Fig. 6. The high contrast resolution of spin echo provides detail demonstrating functional pathology, arterial relationships of the great vessels and anatomy of intracardiac shunts. Fat suppression with inversion prepulses (STIR, or Triple-IR) followed by a TSE readout is important in the characterization of masses (3) and diagnosis of fatty infiltration.

Contrast-enhanced 3D MRA

Contrast-enhanced 3D MR angiography (ce-MRA) has become one of the most efficient and accurate means of assessing complicated cardiovascular anatomy in congenital heart disease (39). A rapid, 3D spoiled gradient echo acquisition is run during the intravenous bolus injection of Gd-based contrast agent. The data acquisition generally takes on the order of 15 sec-20 sec and relies on accurate timing of the scan to the arrival of contrast agent in the vasculature of interest. Timing accuracy is achieved by a number of different methods. A rapid 2D T1-weighted GRE sequence is typically run to detect the arrival time of contrast agent, either as a pre-scan using a small test bolus of contrast agent or immediately preceding the 3D MRA which is manually or automatically triggered when the contrast agent arrives. The resulting high resolution 3D dataset can be processed in a number of ways to evaluate vascular anatomy. Multi-planar reconstruction (MPR) tools can be used to retrospectively generate 2D slices of any orientation from the original 3D data. Maximum intensity projection or volume rendering can be applied to preserve and display the three-dimensional aspect of the data, facilitating the visualization of overlapping anatomical structures.

Like any other MRI of the chest, ce-MRA images of the heart and great vessels can be corrupted by cardiac motion artifact. Some cardiac motion artifacts are evident in the un-triggered



Figure 7. MRA is essential in the assessment of the cavopulmonary flow paths in the palliated single ventricle patient. Reformatted MRA images in a patient with tricuspid atresia demonstrated a classic Glenn (arrow; A) and anastomosis of the right atrium to the left pulmonary artery (B).

3D MRA results shown in Fig. 7. ECG synchronization of ce-MRA has been shown to significantly reduce cardiac motion artifact (40) but at the expense of increased scan time due to the dead-time introduced each heart-beat by prospective triggering. Figure 8 shows an ECG-triggered MRA result with artifactfree visualization of cardiac structures in MPR and volume rendered reconstructions. Breathing motion can also cause blurring in patients unable to breath-hold; however, the shallow regular breathing pattern of infants and small children generally results in good image quality even without breath-hold.

Time-resolved 3D MRA is an angiographic technique designed to provide dynamic information with a temporal resolution of 0.5 sec–3.0 sec (41). In order to achieve this acquisition speed in 3D imaging, through-plane spatial resolution is sacrificed, parallel imaging acceleration and data sharing techniques



Figure 8. ECG-triggered contrast-enhanced 3D MRA. ECG synchronization provides clear visualization of cardiovascular anatomy in and around the heart. Images are shown of patient with doubleinlet left ventricle status-post lateral tunnel Fontan repair who underwent implantation of an 8 mm Amplatzer Septal Occluder (ASO) device (arrow) for a residual leak in the lateral tunnel associated with significant desaturation. Reformatted image in the sagittal plane (A) demonstrates the cavopulmonary is not obstructed. Volume rendered reconstruction of the same data (B) shows artifact free depiction of aortic root.



Figure 9. Dynamic MRA imaging in the sagittal plane in patient with d-transposition of the great arteries status-post Mustard repair. ECG-triggered acquisition with complete 3D volume obtained each cardiac cycle. Selected images from the time series are shown, beginning with the upper left image and proceeding in time across the top row and then the bottom row of images. After intravenous injection of 6 mL of gadolinium into the arm, the superior vena cava is initially visualized. However, complete obstruction of the superior limb of the baffle is suspected due to reflux of contrast into the azygous venous system. The venous system is seen decompressing through collaterals that communicate with the inferior vena cava. Contrast returns to the systemic venous pathway inferiorly, eventually reaching the pulmonary arteries. Contrast finally opacifies the systemic right ventricle and anteriorly located aorta.

such as TRICKS (32) or TREAT (33), and have all been applied. The result is an acquisition which requires only a small dose of contrast agent and can capture the dynamics of blood flow through the right and left circulation, as seen in the example images shown in Fig. 9. This technique has been described using sensitivity encoding in imaging the thoraco-abdominal vessels in pediatric patients (34), and may be important in the assessment of aberrant circulation patterns.

Coronary MR angiography (MRA)

The primary advantages of coronary MRA over X-ray catheter angiography are that it is non-invasive and does not expose the patient to ionizing radiation. These features are particularly important in pediatric patients, motivating the continued development of the technology. Non-invasive coronary angiography by X-ray computed tomography (CTA) is gaining in clinical importance but also carries the risks of X-ray exposure.

Coronary MRA has proven to be technically challenging due to the small size of the vessels and the effects of cardiac and respiratory motion. The most common imaging strategy used currently is a segmented, ECG-triggered 3D SSFP sequence with data acquisition timed to the relatively quiescent phase of mid-diastole. Navigator-echo respiratory gating is used both to avoid respiratory motion, as well as to prospectively adjust slice position based on diaphragm position. While coronary MRA is still in an active state of technical development, it has found important pediatric applications in the assessment of anomalous coronary artery origins (25), and in the serial evaluation of coronary artery aneurysms in Kawasaki disease patients (24).

Cardiac function

Cine imaging of cardiac function and flowing blood forms the primary component of any MRI evaluation of a patient with congenital heart disease. Assessment of global and regional wall motion, as well as accurate quantification of ventricular mass, ejection fraction, stroke volume, and cardiac index, all rely on cine MRI. One of the advantages of MRI over echocardiography is its ability to reproducibly and accurately acquire parallel images in any orientation, eliminating geometrical assumptions in the quantification of cardiac mass and volumes. This advantage is especially important in congenital heart disease which may result in ventricular anatomy which does not fit the usual shape assumptions. One example is the unique ability of cardiac MR to determine ventricular indices in the single ventricle patient (either right or left ventricular morphology). The single ventricle has a bizarre shape which is difficult to model mathematically and does not allow for the geometric assumptions necessary to calculate mass, volume, or cardiac performance from a single image plane (42). The ventricular geometry and performance in the single ventricle throughout all three stages of Fontan reconstruction have been studied using cine MRI (43). Compared to other noninvasive imaging tools, cardiac MR provides a precise assessment of ventricular volumes and function necessary for early post-operative as well as long-term follow-up of these complex patients. The use of MR has also has been validated extensively for measuring right ventricular function (44). During a single examination, CMR provides a complete evaluate of right and left ventricular systolic and diastolic function as well as intracardiac and vascular flow.

Assessment of left and right ventricular volumes and function has also been accurately measured using real-time SSFP cine without breath-hold (45). This technique may be useful in patients with severe cardiac dysfunction or cyanosis when repeated breath-holding becomes difficult or in patients too young to cooperate with breath-hold commands. Real-time acquisitions are also insensitive to the image artifacts which typically arise from atrial or ventricular arrhythmias. Parts of the heart may be missed or repeatedly measured because of respiratory motion during real-time imaging. This must be taken into account when reading these images, and can make quantitative evaluation difficult. Examples of breath-hold, segmented cine and real-time imaging are shown in Figs. 10 and 11.

Velocity mapping

Velocity mapping and flow quantification in thoracic blood vessels and across heart valves provides quantitative information critical to the diagnosis and management of congenital heart disease. Important clinical applications for MR velocity mapping include left-to-right shunt evaluation, vena cava and pulmonary



the great arteries in diastole (A) and systole (B).

artery flow in Fontan patients, and peak velocity measurements in stenotic vessels and valves. MR velocity mapping has been well described to assess the presence and severity of shunt lesions (46). Using this method, measurements of blood flow in the pulmonary artery and aorta are obtained simultaneously. Flow profiles in the pulmonary (Qp) and systemic (Qs) circulations can be expressed as a ratio (Qp:Qs). In the presence of a left-toright shunt such as an atrial or ventricular septal defect, the flow in the pulmonary circulation exceeds the systemic circulation. The presence of valvular insufficiency must be taken into consideration, as this imaging technique relies on the calculation of stroke volumes which will be affected by regurgitant flow. Differential pulmonary blood flow can also be easily estimated by MR velocity mapping and may be helpful in the assessment of the patient with stenotic or hypoplastic pulmonary arteries or post-operative assessment of surgical right ventricular-topulmonary artery conduits (47). The estimation of peak velocities and quantification of collateral circulation are helpful in determining the hemodynamic significance of coarctation or other vascular stenoses. The pressure gradient across a coarctation, and therefore its functional significance, can be estimated using the modified Bernoulli equation (48). In patients with coarctation, the presence of greater flow in the distal aorta suggests the presence of collateral circulation from the intercostal arteries and other branches (49). Finally, velocity mapping can be performed to assess the severity of stenosis or insufficiency of the aortic and pulmonary valves. Aortic or pulmonary regurgitation can be quantified directly to estimate the volume of antegrade flow during systole and regurgitant flow during diastole (50). The degree of pulmonary and aortic insufficiency can be determined by measuring flow in the main pulmonary artery and ascending aorta, respectively. The degree of mitral regurgitation can then be calculated by subtracting the flow into the aorta during systole from the flow across the mitral valve into the left ventricle during diastole (51). In the presence of valvular stenosis, velocity mapping can calculate the peak velocity across the valve. The combination of cine MR and velocity mapping provides a direct demonstration of the jet of stenosis or insufficiency, as well as assessment of regurgitant fraction or severity of stenosis in the pediatric patient with valvular dysfunction.

First-pass perfusion

The use of contrast-enhanced magnetic resonance imaging to identify myocardial perfusion, extent and transmurality of ischemia, infarction, and viability has been well described in adults with atherosclerotic coronary artery disease (51–53). Myocardial ischemia and fibrosis can also complicate the long-term outcomes of patients with various forms of complex congenital heart disease (54). MR perfusion measurement techniques in clinical use today are all based on the dynamic imaging of the first-pass through the myocardium of Gadolinium (Gd) based, T1-shortening contrast agents. An intravenous bolus injection of 0.075 mmol/kg and an injection rate of 4 mL/sec are commonly used, although wide variation can be found in injection protocols. Adenosine is used as a coronary vasodilator to create





a blood flow difference between normal coronary beds and those supplied by stenotic vessels. Single-shot images at three to five slice positions are acquired each heart beat. Ultra-fast imaging sequences are necessary to acquire images at this rate. Variations using GRE (55), SSFP (56), and hybrid GRE-EPI (57) pulse sequences have all been described, and parallel acquisition techniques (58, 59) have been used to enhance the performance of first-pass imaging. All commonly used techniques employ a 90 degree saturation preparatory pulse to increase T1-weighting. As the contrast agent passes through the blood pool and myocardial tissue, the T1 is shortened, and the signal enhanced. This firstpass of contrast agent through the myocardium generally takes 20 secs. to 30 secs. from the time of injection. This time defines the length of the scan as images must be acquired throughout the passage of contrast agent through the myocardium. Ischemic regions with poor perfusion will not enhance at the same rate as normally perfused tissue and can be visualized as regions of transient dark signal.

Although the reported application of MRI perfusion imaging in the pediatric population has been limited, preliminary results demonstrate that MRI evaluation of myocardial perfusion and viability is feasible in patients with congenital and acquired pediatric heart disease (60). Advantages of CMR over nuclear scintigraphy include the lack of ionizing radiation, which becomes important in the consideration of stress imaging in young patients who may require lifelong assessment of myocardial ischemia and function. Compared to the nuclear perfusion examination, which may take from two to six hours, the CMR examination generally takes less than one hour to complete. The high spatial resolution of CMR also allows for the detection of smaller perfusion defects (61). This greater spatial resolution of CMR becomes particularly helpful in the pediatric population. In addition, complimentary data such as regional wall motion abnormalities and delayed enhancement to evaluate viability can be obtained in one all-inclusive study. These applications could prove to be useful in the long-term follow-up of patients with

acquired syndromes such as Kawasaki disease, as well as various forms of congenital heart disease including anomalous left coronary artery communicating to the pulmonary artery (ALCAPA) syndrome, anomalous coronaries and complete transposition of the great arteries arterial switch operation (ASO). Further studies are required to address the diagnostic utility and clinical benefit in congenital and acquired pediatric heart disease.

Delayed myocardial enhancement

Gadolinium-based MRI contrast agents in clinical use are all T1-shortening, extra-vascular, extra-cellular agents. These agents rapidly diffuse out of the capillaries and into the interstitial space. Areas of acute or chronic infarction provide a larger distribution volume for these agents when compared to viable tissue. As a result, within 10 minutes after intravenous injection, a greater tissue concentration of contrast agent will be present in infarcted or fibrosed myocardium than in viable tissue. This process of delayed-enhancement may take longer in "no-reflow" zones within regions of acute infarction.

T1-weighted, inversion recovery imaging can be used to differentiate necrotic regions of delayed-enhancement from viable myocardium. Inversion-recovery delayed-enhancement imaging has been shown to be effective in identifying the presence, location, and extent of acute and chronic myocardial infarction (62). The inversion time (TI) is set to null the signal from viable myocardium, to produce images in which necrotic tissue is bright by virtue of its shorter T1. In practice, the optimal TI is based on the dose of contrast administered and the elapsed time between injection and imaging. An example of delayedenhancement consistent with endocardial fibroelastosis in a patient with aortic coarctation is shown in Fig. 12.

The assessment of transmural extent of viability by CMR has diagnostic importance that is not available from other noninvasive imaging techniques. Studies in adults have demonstrated that late gadolinium-enhanced CMR can predict whether regions of abnormal ventricular contraction will improve after revascularization in patients with CAD (53). Initial experience



Figure 12. Delayed enhancement in a patient with corctation of the aorta who had undergone subclavian flap angioplasty but left with severe aortic stenosis demonstrates a pattern of diffuse hyperenhancement in the short axis (A) and vertical long-axis (B) imaging planes consistent with endocardial fibroelastosis.

evaluating this technique in the pediatric population is limited. Infants diagnosed with ALCAPA syndrome demonstrate variability in the extent of irreversible myocardial injury and ventricular dysfunction. The impact of myocardial viability which may direct surgical decisions regarding coronary reimplantation versus cardiac transplantation has been reported utilizing delayed enhancement to detect ventricular infarct and myocardial fibrosis in infants with ALCAPA syndrome and severe left ventricular dysfunction (63).

Assessment of delayed enhancement may become increasingly important in the CMR assessment of both children and adults with congenital heart disease. Recently, the presence of hyperenhancement has been demonstrated in patients with dtransposition of the great arteries who have undergone an atrial switch procedure (64, 65). Further studies are necessary to determine the prognostic importance of these findings.

CONCLUSION AND FUTURE DIRECTIONS

Cardiac MRI hardware and software continue to evolve and advance. High field 3-Tesla whole-body magnets are coming into widespread use at research and teaching hospitals. The higher field strength brings a direct signal-to-noise (SNR) benefit. This gain is especially appealing in pediatric imaging where the high resolution requirements can be limited by SNR. The spin-echo and spoiled gradient echo CMR techniques, including black-blood TSE, GRE cine, velocity mapping, contrastenhanced MRA, and delayed-enhancement, all benefit from the higher SNR at 3T. However, local susceptibility gradients, RF inhomogeneity, and higher RF power deposition, all limit the application of SSFP sequences at 3T. Hybrid GRE-EPI, critical in first-pass perfusion imaging, is also highly sensitive to local field inhomogeneities. Unfortunately, SSFP and GRE-EPI sequences have become mainstays of CMR at 1.5T, so alternative approaches must be developed before clinical CMR can be considered routine at 3T and above.

Advances in RF receiver hardware are driving the application of parallel imaging technology in CMR. Parallel acquisition techniques have come into routine use in cine, velocity mapping, contrast-enhanced MRA, and first-pass perfusion applications. Commercially available cardiac coils utilize from 5 to 12 elements, and acceleration rates are generally limited to factors of 2 or 3. New 32-element coils designed to take advantage of commercially available 32 receiver channel systems are in clinical testing. Initial results are promising, and should enable higher acceleration factors. Coils designed specifically for smaller children will be necessary to take full advantage of this technology in pediatric patients.

Some of the first applications of the exciting new field of interventional cardiovascular MRI are aimed at pediatric and congenital heart disease (66, 67). The combined development of rapid, real-time MRI sequences, together with MR compatible catheters and guidewires, show promising potential for MR guided catheter-based interventions. Besides the obvious advantage of sparing the pediatric patient from X-ray radiation, interventional MRI also offers soft-tissue contrast, and the capability of assessing blood flow and velocity, and tissue perfusion and viability during the course of the procedure. Clinical applications for this rapidly growing field will begin to appear once MR compatible interventional devices are developed and approved for clinical use.

In summary, CMR currently offers a wide range of clinical applications which show distinct advantages in the pediatric population, where invasive exams and X-ray exposure are to be avoided. Many CMR sequences and techniques originally designed for adult imaging have only recently been applied to pediatric patients. It is expected that the same growth and success of CMR recently witnessed in adult cardiology will be seen in pediatric cardiology in the coming years.

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