Advanced MR Imaging Techniques for Evaluation of the Heart and Great Vessels

Jerold L. Boxerman, MD, PhD
Timothy J. Mosher, MD, PhD
Elliot R. McVeigh, PhD
Ergin Atalar, PhD
João A. C. Lima, MD
David A. Bluemke, MD, PhD

A “one-stop shop” for evaluating cardiac disease with magnetic resonance (MR) imaging is progressing toward clinical reality and promises to have a major effect on the care of patients with cardiac disease. T1-weighted conventional spin-echo imaging gated to the cardiac cycle yields good anatomic detail but requires long imaging times and provides only static images of a single cardiac phase. Fast MR imaging with electrocardiographically (ECG) gated, low-flip-angle, segmented k-space gradient recalled-echo (GRE) sequences provides excellent image quality with sufficiently high temporal resolution to “freeze” cardiac motion. Segmented k-space sequences improve on standard ECG-gated GRE sequences by allowing many cardiac phases, or frames of a cine sequence, to be imaged in a single breath hold with prospective cardiac gating. As commercial implementations of segmented k-space imaging become more widely available, the applications of this technique are expanding from research protocols to include many clinical applications in the heart and great vessels. Such applications include evaluation of vascular anatomy (coronary angiography, aortic disease, aberrant vessels, vascular access), cardiac anatomy (congenital anomalies, right ventricular dysplasia, constrictive pericarditis, valvular function), myocardial perfusion, and myocardial wall motion.

Abbreviations: ECG = electrocardiography, GRE = gradient-recalled echo, NVS = number of views per segment, BCA = right coronary artery, 3D = three-dimensional, TR = repetition time, 2D = two-dimensional

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1From the Department of Radiology and Radiological Science (J.L.B., E.R.M., E.A., D.A.B.), Department of Biomedical Engineering (E.R.M.), and Division of Cardiology (J.A.C.L.), The Johns Hopkins University School of Medicine, 600 N Wolfe St, Baltimore, MD 21287, and the Department of Radiology, Milton S. Hershey Medical Center, Hershey, Pa (T.J.M.). Presented as a scientific exhibit at the 1995 RSNA scientific assembly. Received June 18, 1997; revision requested July 22 and received October 2; accepted October 2. Address reprint requests to D.A.B.

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### Definitions of Key Terms Used to Describe the Segmented k-Space Pulse Sequence

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>k</td>
<td>Number of lines, or phase-encoding steps, in an image (y resolution)</td>
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<tr>
<td>R-R interval</td>
<td>Time between heartbeats</td>
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<tr>
<td>Cine frame</td>
<td>The R-R interval is divided into multiple “movie frames” that correspond to different phases of the cardiac cycle</td>
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<tr>
<td>Segment of k space</td>
<td>A segment of k space is collected during each cine frame</td>
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<tr>
<td>NVS</td>
<td>Number of views per segment (ie, number of k-space lines acquired during each frame)</td>
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<tr>
<td>TR</td>
<td>Interval between radio-frequency excitations in a segment or frame</td>
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<tr>
<td>Temporal resolution</td>
<td>Time duration of a segment or frame (NVS · TR)</td>
</tr>
<tr>
<td>Single-section, multiphase mode</td>
<td>Segments of the R-R interval are used to image various temporal phases of the same physical section</td>
</tr>
<tr>
<td>Multisection, single-phase mode</td>
<td>Segments of the R-R interval are used to image one temporal phase of different physical sections</td>
</tr>
<tr>
<td>Trigger window</td>
<td>Fraction of the R-R interval allotted for detection of the next R wave, to which subsequent frames are gates</td>
</tr>
</tbody>
</table>

#### INTRODUCTION

Cardiovascular disease is the leading cause of death in the United States and thus has tremendous economic and social impact. Despite a wide array of available diagnostic techniques, there is a need for improved noninvasive diagnosis of cardiovascular disease. With magnetic resonance (MR) imaging, multiple diagnostic tests of cardiac function and morphology can be performed during a single examination; this capability may make MR imaging cost-effective.

In recent years, several MR imaging techniques for evaluating the heart and great vessels have emerged. T1-weighted conventional spin-echo imaging gated to the cardiac cycle yields black-blood images of the heart and great vessels. Although the anatomic detail is good, the imaging times are relatively long (approximately 5–7 minutes); thus, static images of a single cardiac phase are typically acquired to avoid excessively long imaging times. Cine imaging, in which multiple images are rapidly displayed in a continuous loop, has the advantage of providing functional information (eg, on cardiac wall motion and blood flow) in addition to anatomic detail. Most often, gradient-recalled-echo (GRE) pulse sequences are used to produce bright-blood images of the heart and great vessels. Standard electrocardiographically (ECG)-gated GRE sequences require 3–5 minutes for acquisition of one to four sections with retrospective or prospective cardiac gating (1); such sequences are thus too time-consuming for quantitative assessment of cardiac perfusion or function.

However, modifications to the standard GRE pulse sequence have greatly improved the temporal resolution of the sequence and allowed true cine imaging. Spoiled GRE segmented k-space cardiac sequences, originally described by Atkinson and Edelman (2), allow imaging of many cardiac phases (viewed as frames of a cine sequence) in a single breath hold with prospective cardiac gating. This technique has been used extensively in research protocols for cardiac tagging (3) and evaluation of cardiac perfusion (4, 5) but has been less frequently used in clinical studies (6). As commercial implementations of this technique become more available, the applications of the technique are expanding. In this article, we provide an overview of the segmented k-space pulse sequence and discuss advanced applications of this technique in the heart and great vessels: evaluation of vascular and cardiac anatomy, myocardial perfusion, and myocardial wall motion.

#### SEGMENTED K-SPACE SEQUENCE

The segmented k-space sequence is a fast GRE technique with a relatively short repetition time (TR) (2.5–10 msec) and very short echo time (1–2 msec) (7). The TR and echo time are usually the minimum values achievable with the MR gradient system. A flip angle of 8°–20° is used for most applications. These parameters produce saturation of stationary tissues and flow-related enhancement from inflowing
blood with unsaturated spins. Terms commonly used to describe the segmented k-space sequence are defined in the Table; the sequence is illustrated in Figures 1 and 2.

- **Traversal of k Space**

Because cardiovascular structures (including blood flowing within the great vessels) move in a time frame much shorter than an R-R interval, it is necessary to acquire the lines of k space that make up an image over a relatively short segment of the cardiac cycle. For a TR of 2.5-10 msec and a y resolution (k_y) of 100 lines, the time required to obtain all k-space lines consecutively would consume a substantial part if not most of the cardiac cycle and could even exceed an R-R interval. The resulting images would demonstrate blurring secondary to motion of cardiac structures. These problems are circumvented by spreading image acquisition over several R-R intervals and gating the acquisition of each portion of the image to the same temporal position in the cardiac cycle. The entire image acquisition is usually performed during a breath hold to eliminate artifacts caused by respiratory motion.
The R-R interval is therefore divided into multiple cine frames corresponding to different phases of the cardiac cycle, and a segment of k-space is collected during each cine frame. Multiple radio-frequency pulses are applied during every segment, each pulse corresponds to one line of k-space. The number of k-space lines acquired during each frame is the number of views per segment (NVS). (The abbreviation "NVS" is used in the Sigma FASTCARD software [GE Medical Systems, Milwaukee, Wis], although the concepts apply to all implementations of segmented k-space acquisition.) The number of heartbeats required to acquire all k-space lines of an image is therefore k/NVS. The temporal resolution of the image equals NVS · TR because all lines of k space that make up the image are acquired during the same frame (with duration NVS · TR) of multiple cardiac cycles. For a TR of 3–5 msec and NVS of 5 (high temporal resolution, as used for wall motion analysis) to 64 or even 80 (low temporal resolution, as used for single-shot perfusion imaging), the temporal resolution of each frame ranges from approximately 20 msec to 250 msec or more, depending on the application. As TR decreases with improved hardware, the NVS that is acceptable for a desired temporal resolution increases, thereby decreasing the total number of heartbeats needed to acquire the entire image.

Because multiple lines of k space for each frame are obtained during every R-R interval, the total imaging time needed to acquire an entire frame decreases by a factor of NVS. In this regard, NVS is analogous to the turbo factor or echo train length in fast spin-echo imaging. Similarly, large values of NVS, like large echo train lengths, result in image blurring because the temporal resolution of each frame equals NVS · TR. As NVS increases, the temporal resolution of each frame decreases; the resulting images of rapidly moving cardiovascular structures are much more susceptible to blurring. However, increasing NVS decreases the total imaging time needed to acquire the entire frame. Thus, there is a trade-off between temporal resolution and total imaging time for a frame. Moreover, as NVS increases, the number of frames available for cine display decreases correspondingly.

Sample parameters for a segmented k-space sequence are as follows: For a y resolution of 128 lines (128 lines of k space) and NVS = 8, 128/8 = 16 R-R intervals are needed to completely acquire the image (complete all phase-encoding steps). At a heart rate of 60 beats per minute (R-R interval = 1,000 msec), the total breath-hold time is 16 seconds. If TR = 5 msec, the temporal resolution of one cine frame is 40 msec (NVS · TR). The remaining 960 msec of the cardiac cycle can be used to collect other lines of k space corresponding to different cardiac phases (single-section, multiphase mode) or other section locations (multisection, single-phase mode). In actuality, not all of the R-R interval may be available for acquiring lines of k space. A trigger window (typically 10%–20% of the cardiac cycle) during which no image acquisition occurs is used in some pulse sequences exclusively for detecting an R wave, to which subsequent image frames are gated. Large windows generally yield more robust triggering but decreased acquisition time. The trigger window has been circumvented in some implementations (8).

- **Single-Section, Multiphase Acquisition**

Single-section, multiphase acquisition is useful in studying the dynamics of a particular imaging section throughout the cardiac cycle. For example, this mode is used in cardiac tagging studies to elucidate the myocardial strain patterns throughout systole and in visualizing blood flow patterns in aortic dissection. The fundamental characteristic of this mode is that the acquired images reflect various cardiac phases of the same imaging section (Fig 1).

For the temporal resolution of 40 msec described earlier, the maximum number of cardiac phases is approximately 25 frames (less trigger window requirements) and depends on the heart rate. If NVS is increased from 8 to 16, the number of available cardiac frames will be reduced to about 12 and the total acquisition time will decrease from 16 to 8 R-R intervals, but the cine display will appear less smooth because of the concomitant decrease in temporal resolution. Typically, a 10°–15° flip angle is used for single-section, multiphase studies with an intersection spacing of 0°–20° of the section thickness. The "view sharing" technique allows interpolation in time between cardiac movie frames and can be used to double the number of frames available for cine display (8).
• **Multisection, Single-Phase Acquisition**

Multisection, single-phase acquisition is useful in performing an anatomic survey without regard to particular phases of the cardiac cycle. In this situation, the objective is to maximize the rate of acquisition of multiple sections. Additional sections are acquired, although each is acquired at a different phase of the cardiac cycle. For example, this mode is used to rapidly survey the aorta in cross section during a single breath hold in cases of suspected aortic dissection or to study anomalous vascular anatomy. By using a very high NVS (eg, 32 or 64) with multiple signals averaged to reduce motion artifact, multisection acquisition can be performed in uncooperative or ill patients with a reduced breath hold (only approximately 2–6 seconds) at the expense of a limited number of sections. The fundamental characteristic of this mode is that the acquired images reflect different imaging sections at different phases of the cardiac cycle (Fig 2). In addition, unlike the TR for single-section, multiphase acquisition, the effective TR for low values of NVS is on the order of the R-R interval in multisection, single-phase acquisition; thus, image contrast is different in the two acquisition modes.

• **Practical Considerations**

**Coil Selection and Placement.** A phased array surface coil allows increased bandwidth (±32 kHz or greater) with adequate signal-to-noise ratio. Increased bandwidth reduces the minimum TR and echo time values and allows more lines of k space to be collected per unit time. Coil placement greatly affects the quality of the examination; optimal results are obtained when the coil is centered around the heart.

**ECG Triggering.**—The quality of the ECG gating is of utmost importance for the success of the study. Optimally, the imager should trigger every R-R interval. If the patient’s heart rate changes during the examination, NVS and y resolution must be adjusted so that imaging does not extend beyond the trigger window because missing ECG triggers may waste substantial imaging time. As a corollary, patients with arrhythmia impose an additional limita-

• **Segmented k Space and Echo planar Hybrid Techniques**

The imaging speed of the standard segmented k-space technique may be further improved by sampling additional echoes with extra readout gradient lobes, as in echo-planar imaging. For instance, each additional readout lobe requires approximately 2 msec extra per radio-frequency excitation but halves the total number of TR excitations required, thereby reducing the overall imaging time by 30%–40%. Acquiring additional echoes per TR excitation further reduces the imaging time. Therefore, for fixed NVS (constant breath hold), the temporal resolution (NVS · TR) improves because the effective TR per line of k space decreases. Alternatively, for a given temporal resolution, the breath hold can be reduced because NVS can increase to offset the decreased effective TR.
Hybrid spoiled GRE and echo-planar imaging reduces several of the difficulties associated with standard single-shot echo-planar imaging yet maintains some of the speed advantage. Single-shot echo-planar images obtained in one heartbeat are very susceptible to severe artifacts caused by field inhomogeneities, chemical shift, and motion. However, with a hybrid sequence, the shorter echo time reduces image distortion due to susceptibility differences, ECG gating with shorter temporal resolution helps minimize motion-induced blurring of the heart, and flow sensitivity is inversely proportional to the number of interleaves or echoes per excitation. Hybrid spoiled GRE and echo-planar imaging (9–11) represents a compromise between the speed and high signal-to-noise ratio of echo-planar imaging and the robust image quality and reproducibility of spoiled GRE imaging.

**APPLICATIONS**

- **Evaluation of Vascular Anatomy**

  **Coronary Angiography**—Clinical applications of existing coronary MR angiographic techniques (12,15) include determining the patency and direction of flow in native coronary arteries (14,15), assessing the patency of coronary artery bypass grafts (10) and native vessels after coronary stent placement (17), evaluating congenital and acquired coronary variants (18), following the progress of known proximal lesions (eg, after treatment with angioplasty), and identifying anomalous coronary arteries and their anatomic courses (19). Coronary MR angiography can also be used to screen and evaluate patients with ischemic heart disease and coronary artery disease. Several clinical comparisons between coronary MR angiography and conventional cardiac angiography have been performed (15,20–22). However, no technique has yet emerged that has sensitivity and specificity for lesion detection equal to those of conventional angiography, although preliminary clinical studies appear promising. Coronary MR angiography can routinely demonstrate the proximal and middle portions of major coronary arteries and some coronary artery branches in most patients. Current limitations of coronary MR angiography include an inability to demonstrate the distal portions of the coronary arteries and their branches. At the current stage of development, coronary MR angiography may be most helpful for excluding clinically important stenoses in patients referred for diagnostic angiography. As techniques improve, coronary MR angiography may become an integral part of the evaluation of patients with ischemic heart disease.

  Respiratory and cardiac motion, along with the small caliber and tortuosity of the coronary arteries, make coronary MR angiography a technical challenge. Segmented k-space acquisition with ECG gating and breath holding to minimize artifacts from cardiac motion and respiratory motion, respectively, has made coronary MR angiography possible. The low flip angle and short TR of segmented k-space acquisition and the use of fat suppression to eliminate epicardial fat produce a good time-of-flight
Figure 4. Three-dimensional coronary MR angiography with navigator echo-based retrospective respiratory gating. (a) Image shows diaphragm tracking with navigator echoes. The dotted line (arrow) represents the track of the diaphragm at the interface of the lungs (above line) and liver (below line). Segments of k space are acquired during successive heartbeats. If the segment is acquired at an acceptable diaphragm position, the segment is used to construct the appropriate section; otherwise, the segment is rejected and not included in image construction. (b) Sample 3D MRI angiogram shows bifurcation of the left main artery into the left anterior descending and left circumflex (arrow) arteries. (c, d) Sample 3D MRI angiograms show the ostium of the RCA (arrow in d).

Effect that accentuates the coronary arteries. Both two-dimensional (2D) and three-dimensional (3D) techniques are used. Atkinson and Edelman (2) and Edelman et al (23) pioneered 2D time-of-flight single-breath-hold cardiac-gated imaging with the spoiled GRE segmented k-space technique (NVS = 8, k1 = 128, 16-heartbeat acquisition). Oblique 4-mm-thick sections were acquired in midventricle to minimize heart motion and maximize coronary flow. Later improvements included spectrally selective radiofrequency pulses to suppress epicardial fat and a surface coil to increase signal-to-noise ratio. Similar 2D techniques have been used for spiral imaging with interleaved spiral trajectories through k space (24), which provide high temporal and spatial resolution with relative insensitivity to flow artifacts and motion artifacts.

Tortuosity of vessels makes selection of 2D imaging planes difficult. Anatomic approaches comparable with those used in conventional angiography and echocardiography have been particularly useful (25). To image the right coronary artery (RCA), a transaxial section through the left and right ventricles is used to select an oblique plane through the right ventricle, which transects the RCA at two points. This oblique image is used to select a plane through the anterior atrioventricular groove, which contains the RCA. Scout imaging for section location is typically performed with a high NVS (short breath hold) and multisection, single-phase acquisition for identification of gross landmarks. Once the vessel plane is determined, low-NVS imaging with multiphase, single-section acquisition within one breath hold is performed. Cine display of the images is used for better visualization of the coronary arteries (Fig 5) (26). Parallel overlapping sections are obtained to cover tortuous vessels. Oblique (25) as well as fixed transverse planes have been used to image the left main artery and left anterior descending artery.

In non-breath-hold 3D MR angiography, navigator echo-based retrospective respiratory gating and respiratory triggering are performed (22,27) based on the superior-inferior position of the diaphragm (Fig 4). Thin, contiguous sections are acquired with less partial-volume effects and more accurate vessel size estimation than in 2D imaging. The 3D technique has several advantages over 2D imaging, including higher spatial resolution, increased signal-to-noise ratio, continuous coverage of the coronary arteries, capacity for multiplanar reconstruction after processing, and suitability for use in patients who cannot meet breath-holding requirements. A 3D volume acquisition is also less operator dependent than iterative 2D approaches, which require multiple oblique
Figure 5. Type B aortic dissection in a 46-year-old man. (a) MR image from a multiphase, single-section sagittal oblique cine acquisition shows the dissection (black arrow), which begins just distal to the left subclavian artery. On other views, the dissection extended into the abdomen to the level of the renal arteries. The decreased signal intensity in the false lumen (white arrow) is due to slow flow and in-plane flow. On cine images, signal intensity changes synchronous with the cardiac cycle allowed differentiation of slow flow in the false lumen from thrombus. (b) Multisection, single-phase transverse cine MR images show the aorta from just below the origin of the celiac trunk (straight arrow in top left image) down to the origin of the superior mesenteric artery (bottom right image). The celiac trunk emerges from the true lumen; this finding is better demonstrated on superior sections. The superior mesenteric artery also arises from the true lumen and is not involved by the dissection (curved arrow in top right image).

Prescriptions. However, 3D imaging of the entire heart in three acquisition slabs takes approximately 30 minutes or longer, which may be substantially longer than the time needed for 2D imaging. Irregular breathing patterns may be problematic; the accuracy with which the diaphragm is tracked greatly affects whether the coronary arteries are imaged at a constant position.

Aortic Dissection.—A common indication for MR imaging of the aorta is aortic dissection, which occurs most often in hypertensive middle-aged men with atherosclerotic disease or younger patients with underlying connective-tissue disorders (eg, Marfan syndrome). MR imaging is used to determine whether the dissection involves the ascending aorta (Stanford type A, DeBakey class I and II) or descending aorta (Stanford type B). Type A disease may occlude the coronary arteries or aortic branch vessels and rupture into the pericardium, resulting in cardiac tamponade and death; such cases are therefore considered for emergency surgery. Type B disease (dissection of the distal arch beyond the origin of the left subclavian artery) is managed medically with antihypertensive agents. Aortic insufficiency is a complication of aortic dissection and, if severe, may require valve replacement.

Traditional MR evaluation of aortic vasculopathy involves spin-echo T1-weighted imaging for anatomic depiction and GRE flow-compensated bright-blood imaging with flow-related enhancement roughly proportional to the velocity of flowing blood (28). Single-level GRE imaging can be performed without cardiac gating, with each image obtained during a 10–15-second breath hold (eg, with TR = 30 msec, R = 192, and two signals acquired). Imaging the entire chest takes 3–4 minutes plus additional time to allow the patient to breathe between acquisitions. Traditional gated GRE imaging also takes 3–4 minutes for a full cine sequence containing one to four sections. Distinguishing slow-moving blood from thrombus
or atherosclerotic plaque on T1-weighted and nongated GRE images is a common problem. Intravenous injection of exogenous contrast agents combined with 3D GRE imaging has yielded excellent anatomic images of the aorta; this technique is based on the T1 shortening of blood rather than on flow (29). Fast low-angle shot imaging with 3–5 mL of gadolinium contrast material injected per imaging plane has also been advocated for evaluation of aortic dissection (30,31).

Segmented k-space imaging allows display of flowing blood through multiple phases of the cardiac cycle, as well as rapid screening of the length of the aorta for involvement of branch vessels, and is a useful adjunct to conventional MR imaging (Fig 5) (32–34). Multi-phase, single-section segmented k-space images allow reliable identification of flowing blood due to cyclic change in signal intensity during the cardiac cycle (35–37). For rapid verification of flowing blood, eight or more cardiac phases can be imaged in a single breath hold; data from these phases can be combined to create maximum- or minimum-intensity projection images for definition of the dissection plane. Rapid image acquisition with a segmented k-space technique is particularly beneficial for evaluation of ill patients or patients in potentially unstable condition in the acute setting. Single-phase, multisection acquisition with multiple (eight to 12) signals averaged may allow rapid screening in patients for whom breath holding is not possible (eg, sedated or uncooperative patients) (Fig 6).

The appearance of intramural hematoma of the thoracic aorta without an intimal tear is similar to that of a typical aortic dissection (38). However, T1-weighted images show a crescent-shaped area within the aortic wall instead of a distinct intimal flap. The intramural hemorrhage in aortic dissection has variable signal intensity, which presumably depends on the age of the hemorrhage. The signal intensity is often medium to low, which can make it difficult to distinguish intramural dissection from mural thrombus or even slow flow on T1-weighted images. Single-phase, multisection segmented k-space images allow rapid interrogation of multiple sites along the aorta. Cine images demonstrate an absence of cyclic changes in signal intensity within an intramural hematoma.
Aortic Coarctation.—Coarctation of the aorta, a symptomatic congenital lesion of the aortic arch, is commonly evaluated with MR imaging. The coarctation usually occurs at the junction of the ductus arteriosus and aortic arch, just distal to the origin of the left subclavian artery. Aortic coarctation is usually diagnosed clinically; MR imaging is used to evaluate the location and length of the coarctation, the status of the aortic isthmus (the watershed zone between the left common carotid and left subclavian arteries), and the degree of collateral circulation. Morphologic changes in the aorta, including focal narrowing of the proximal descending aorta with poststenotic dilatation, are best observed on oblique sagittal images (Fig 7a). Single-section, multiphase segmented k-space images can help assess the hemodynamic significance of the coarctation by demonstrating an altered flow pattern and a jet of signal void distal to a physiologically significant coarctation (Fig /b).

Aberrant Vessels.—The most common congenital abnormalities of the aortic arch include right-sided aortic arch with mirror-image branching or an aberrant left subclavian artery, double aortic arch, and left-sided aortic arch with an aberrant right subclavian artery. In children with a suspected vascular ring, respiratory abnormalities and dysphagia are common indications for MR imaging. Although spin-echo T1-weighted images often provide sufficient anatomic information for diagnosis, bright-blood, flow-sensitive images may help confirm vascular position in very small children, in whom spin-echo T1-weighted resolution is limited (Fig 8).
Figure 8. Possible aberrant vessels in a 5-year-old girl with a right-sided aortic arch (found during work-up of a liver laceration). (a) Spin-echo T1-weighted transverse MR image shows a right-sided aortic arch and an apparent small diverticulum in the descending aorta (solid arrow); the latter finding is suggestive of an aberrant left subclavian artery. Presence of an aberrant left subclavian artery could not be determined from the spin-echo images. Arrowhead = ascending aorta, open arrow = narrowed trachea. (b) Multi-section, single-phase transverse cine MR images (displayed from superior [top left] to inferior [bottom right]) show mirror-image branching with a left brachiocephalic trunk (arrowhead), right common carotid artery (open arrow), and right subclavian artery (solid arrow) arising from the aortic arch; no aberrant vessels are present. This morphology has a high association with other congenital heart defects, although none were found in this case.

Vascular Access.—Patients with long-term implantation of central venous catheters frequently develop thrombi in central veins, and accurate noninvasive imaging is useful in identifying patent central veins for future access. The role of radiology and the interventional radiologist in the care of patients who require long-term venous access is expanding to include multimodality imaging for anatomic evaluation, guided catheter placement or repositioning, and diagnosis and treatment of catheter occlusion or related venous thrombosis (39,40). Interventional procedures have been developed for relief of venous obstruction, repositioning of catheters, and placement of unconventional access devices (40).

MR angiography can provide diagnostic-quality images of the internal and external jugular, brachiocephalic, subclavian, axillary, femoral, and iliac veins and the superior and inferior vena cava. Conventional 2D time-of-flight imaging with nonsegmented k-space acquisition has been used to identify potential venous access sites and directly influence therapy (39). In our experience, segmented k-space imaging is extremely useful for obtaining bright-blood images of major veins in the chest and neck (Fig 9). The gated rapid imaging technique substantially reduces arterial pulsation-induced artifacts in the adjacent major venous structures.
In addition, single-phase, multisection segmented k-space acquisition can be performed with multiple (eight to 12) signals averaged to further reduce motion artifact in sedated patients, for whom breath holding is not possible.

- **Evaluation of Cardiac Anatomy**

**Congenital Anomalies.**—Segmented k-space techniques can be used to demonstrate cardiovascular function and flow in patients with repaired or untreated congenital heart disease. Particularly when the images are displayed in a cine loop, single-section, multiphase sequences are useful for visualization of surgical anastomoses and conduits and detection of stenosis, regurgitation, and left-to-right shunts. Multisection cine GRE imaging is suitable for measuring global right ventricular function, an important issue in congenital heart disease. The ability to demonstrate complex cardiac anatomy and allow measurement of cardiac function and flow in one examination makes MR imaging a useful comprehensive tool for follow-up of congenital heart disease (41). Cine MR imaging is also a suitable noninvasive means of quantifying ventricular volume in children with complex congenital heart disease (42).

Ventricular septal defects are one example of a congenital cardiac defect that can be evaluated with segmented k-space imaging (Fig 10). Conventional spin-echo imaging in the axial and oblique planes yields en face views of the interventricular septum and therefore allows purely anatomic evaluation (43–45). Detection with cine imaging of the signal void created by jets of shunted blood allows identification and confirmation of small ventricular septal defects that may otherwise be obscured by cardiac motion. Cine imaging allows detection of shunt flow, which is hypointense relative to the surrounding blood flow, and enables not only accurate anatomic evaluation of cardiac structures but functional assessment of the cardiac chamber, wall topology, and flow relationships (46).
Figure 10. Large ventricular septal defect in a 30-year-old man who underwent correction of transposition of the great vessels. (a) Spin-echo T1-weighted MR image shows dextroversion of situs solitus and a large ventricular septal defect (open arrow) through the membranous part of the septum and the adjacent muscular part. The morphologic left ventricle (solid arrow) is slightly anterior to the right ventricle, and the trabeculation pattern and morphology of both ventricles are similar. The right ventricular hypertrophy is secondary to severe pulmonic stenosis, which was demonstrated with catheterization and seen on the cine MR images (not shown). (b) Single-section, multiphase coronal cine MR images obtained from the beginning (top left) to end (bottom right) of systole also show the septal defect between the right and left ventricles (arrowhead). A low interventricular pressure gradient accounts for the lack of a left-to-right turbulent jet. Arrow = aorta.

Right Ventricular Dysplasia.—Arrhythmogenic right ventricular dysplasia is a primary disorder of the right ventricle characterized by partial or total thinning and replacement of muscle by adipose or fibrous tissue and enlargement of end-diastolic diameter (47). Fat extends from the epicardial surface through the interstitium and displaces myocardial fibers. Reduced fractional shortening in the right and left ventricles, trabecular disarray, and segmental wall motion abnormalities, bulges, and aneurysms also occur in some patients (48). Most individuals, however, have regional segmental right ventricular thinning and akinesia or dyskinesia and present with ventricular fibrillation or ventricular tachycardia. Inheritance patterns suggest that right ventricular dysplasia is autosomal dominant with variable expression and penetrance. Right ventricular dysplasia is found predominantly in males, and symptoms frequently occur with exercise.

Right ventricular dysplasia must be differentiated from right ventricular outflow tract tachycardia, which is associated with a substantially lower risk of sudden death, and from nonpathologic fatty infiltration, which usually does not cause clinical symptoms. Diagnosis is based on identification of specific anatomic and functional abnormalities of the right ventricle. Right ventricular angiography is considered the standard of reference but cannot demonstrate pathologic structural changes in the myocardium. MR imaging has recently shown promise in clarifying the diagnosis of right ventricular dysplasia and can provide useful information about cardiac function, regional wall...
motion, and myocardial thinning and fatty infiltration of the right ventricular free wall (49-51). In patients with right ventricular dysplasia, the right ventricle may appear normal or dilated and the free wall may appear globally thinned or have focal areas of marked myocardial thinning. T1-weighted images demonstrate increased myocardial signal intensity due to fatty infiltration. Breath-hold cine imaging is used to identify focal or global wall motion abnormalities (Fig 11). Localization of dyskinesia to the right ventricular outflow tract helps distinguish right ventricular outflow tract tachycardia from right ventricular dysplasia (52).

**Constrictive Pericarditis.**—Patients with constrictive pericarditis present with a clinical picture suggestive of congestive heart failure; diagnosis is based on a hemodynamic pattern that reveals impaired ventricular filling. Diastolic filling is impaired by thickening and fibrosis of the pericardium with elevated pressure in the atria and ventricles. Causes include antecedent viral pericarditis, infiltration by neoplasia or collagen vascular disease, irradiation, trauma, and surgery. Clinically, it is necessary to distinguish constrictive pericarditis, which is treated with pericardiectomy, from restrictive cardiomyopathy, which is treated medically and is often due to endomyocardial fibrosis, amyloidosis, sarcoidosis, hemochromatosis, or tumor involvement. Pericardial thickening is the most useful MR imaging finding for diagnosis of constrictive pericarditis and exclusion of restrictive cardiomyopathy, although patients who have undergone cardiac surgery can have pericardial thickening without constrictive disease. Echocardiography is less accurate than MR imaging in assessment of pericardial thickness. Constrictive pericarditis and restrictive cardiomyopathy have similar hemodynamic profiles at cardiac catheterization.
Spin-echo MR imaging allows detection of a thickened pericardium (>4 mm thick) with an accuracy of 95% in patients with confirmed constrictive pericarditis (53). The pericardium typically appears as a low-signal-intensity band due to the fibrocalcific nature of the pericardial contents (54,55). Sagittal and coronal cross sections show the nonuniformity of the pericardial thickening. T1-weighted images may show large pericardial effusions and edema. Other findings include narrow, tubular ventricles and a sigmoid septum. Dilatation of the right atrium, inferior vena cava, or hepatic veins is a less specific finding and also occurs in patients with restrictive cardiomyopathy (53). Cine MR imaging has recently been used for assessment of pericardial disease (55,56) and provides dynamic information that may suggest a diagnosis of constrictive pericarditis, such as diminished ventricular filling and abnormal movement of the ventricles against thickened pericardium (57) (Fig 12).

Valvular Function.—Cine MR imaging can demonstrate abnormal patterns of blood flow associated with stenotic or insufficient valves, as well as the morphologic sequelae of valvular disease, such as chamber dilatation and hypertrophy (58). Although valvular function is primarily assessed with echocardiography, MR imaging is useful for characterizing valvular disease in the context of an integrated cardiac examination.
Cine segmented k-space sequences are sensitive to altered patterns of blood flow around normal and diseased valves; when the images are displayed in a cine loop, such sequences allow visualization of stenosis and regurgitation (Fig 13) (41). Whereas laminar, coherent blood flow in the cardiac chambers has increased signal intensity compared with that of surrounding myocardium, turbulent, high-velocity jets through dysfunctional valves produce oblong, fan-shaped signal voids due to dephasing of turbulent spins and cancellation of net signal. The presence and extent of a turbulent jet on an image are highly dependent on the chosen echo time and whether flow compensation was used. In severe aortic stenosis, the postvalvular velocity can exceed 500 cm/sec. In normal individuals, transient focal signal voids lasting less than 100 msec may be seen at the tips of valve leaflets and by valve anuli but do not persist throughout systole or diastole, unlike the signal voids due to valvular disease.

- **Evaluation of Myocardial Perfusion**

  Contrast-enhanced MR imaging is becoming increasingly useful for assessing microvascular perfusion. Early studies in which spin-echo imaging was used required several minutes for acquisition of each image (59), and the regional increase in signal intensity observed on spin-echo T2-weighted images resulted from edema formation, which took several hours to develop (60). More recently, myocardial perfusion has been assessed in animals (5) and humans (61,62) by rapidly imaging the first pass of extravascular paramagnetic contrast agents such as gadopentetate dimeglumine and characterizing the enhancement patterns that occur during the first 1-2 minutes after administration of contrast material (63). The myocardial territory corresponding to areas of microvascular occlusion has reduced signal intensity (hypoenhancement) compared with that of normal myocardium immediately after administration of contrast material (Fig 14) (5). In reperfused infarcts, myocardial signal intensity is increased (hyperenhancement) (Fig 15) (63,64). The ability to discern these changes with fidelity may
Figures 14, 15. (14) Occlusion of the circumflex artery in a 56-year-old man who underwent streptokinase therapy with partial resolution of symptoms. (a) Cine MR image from the first pass of a magnetization-driven spoiled GRE perfusion study shows a subendocardial zone of hypoenhancement (arrow) within the 1st minute after administration of contrast material. The hypoenhanced area extends toward the epicardium and corresponds pathologically to a region with microvascular obstruction and delayed delivery of contrast agent. (b) Corresponding thallium scan shows a fixed defect (arrow) that anatomically matches the hypoenhanced region on the MR image. The defect on the thallium scan is slightly larger than the area of microvascular obstruction on the MR image. Arrowhead = ventricular septum. The patient underwent rescue percutaneous transluminal coronary angioplasty.

(15) MR myocardial perfusion study in a canine model. The left anterior descending coronary artery was occluded for 90 minutes with a balloon catheter, and the heart was then reperfused for 48 hours. (a) Photograph of the heart after staining with triphenyltetrazolium chloride shows absence of stain (infarction) in the endocardial territory of the left anterior descending coronary artery (arrow). (b) Delayed-phase MR image obtained with a magnetization-driven spoiled GRE technique approximately 10 minutes after bolus injection of gadopentetate dimeglumine shows endocardial hyperenhancement (arrow) in a region that anatomically matches the region of infarction in a. (Courtesy of Carlos Rochitte, MD, The Johns Hopkins University, Baltimore, Md.)
play a role in the detection of myocardial infarcts and determination of their size.

First-pass myocardial perfusion sequences must be capable of rapidly establishing T1 contrast for multiple sections with high temporal resolution (usually one to two heartbeats). Early segmented k-space approaches typically used single-section inversion-recovery (inversion-recovery–fast low-angle shot) techniques (4,5,65); multisecton inversion-recovery preparatory sequences were later developed (66). Because the relationship between signal intensity and 1/T1 for inversion-recovery preparatory sequences is largely non-linear, particularly in the blood, a single-section magnetization-driven spoiled GRE technique was developed that drives magnetization to steady state with a train of “dummy” radio-frequency pulses before imaging with a 45° flip angle (67). This technique broadens the range over which signal intensity is linearly related to 1/T1 and contrast agent concentration. The magnetization sampled by inversion-recovery and magnetization-driven spoiled GRE sequences depends on the extent of T1 relaxation during the previous RR interval and is thus dependent on heart rate. “Arrhythmia-insensitive” perfusion sequences make use of saturation recovery with a 90° saturation pulse (68,69) to eliminate the sensitivity of image contrast to fluctuations of cardiac rhythm and rate.

Myocardial Tagging
Myocardial motion is an excellent indicator of coronary stenosis, and wall motion abnormalities are extremely localized to ischemic and infarcted myocardium and actually precede both ECG abnormalities and chest pain as an indicator of myocardial ischemia. To measure cardiac wall motion, it is necessary to track markers on the myocardium throughout the cardiac cycle. Myocardial tagging is an MR imaging technique for presaturating thin planes of myocardium before imaging with a sequence of radio-frequency pulses. Dark lines appear on the MR image where the tagging planes intersect the orthogonal imaging plane. The tags persist in the myocardium during the cardiac cycle, deforming with the myocardium as it contracts during systole and expands during diastole; and images perpendicular to the tag planes can therefore be used to track the motion of the tags and the underlying myocardium. Because the MR tags relax with the T1 of the heart, they must be regenerated at the onset of each contraction but persist beyond systole.

To facilitate postprocessing segmentation of the myocardium from the blood pool, black-blood imaging may be used by presaturating the blood pool immediately above and below the imaging section at end-diastole and inverting the spins in the atrial and pulmonary blood before diastolic filling. These techniques darken the ventricular blood with respect to the myocardium and make it easier to distinguish the myocardium from the blood pool. Postprocessing software allows accurate estimation of tag displacement to within 0.1 mm (70,71), and the temporal evolution of tag displacement can be mathematically processed to compute 3D myocardial strain maps (Fig 16) (72,73). During systole, normal myocardium thickens in the radial direction and shortens in the circumferential direction (73). The eigenvectors and eigenvalues of the 3D strain tensors describe the directions and magnitudes of maximal thickening and shortening and can be used to quantify the mechanical behavior of the myocardium.

Tagged cine segmented k-space MR imaging studies (3) have been applied to 2D (74) and
3D (75,76) cardiac stress testing in an effort to overcome technical limitations of transthoracic echocardiography, including moderate image quality and lack of quantitative results. In response to intravenously administered dobutamine, wall motion abnormalities can be induced in coronary beds supplied by arteries with subcritical stenoses (77). These wall motion abnormalities have high sensitivity and specificity for ischemic heart disease. Myocardium that is dysfunctional at rest but responds to inotropic stimulation is deemed to be hibernating myocardium and may benefit from revascularization therapy (78).

The 2D and 3D dobutamine stress tagging protocols at our institution involve short- and long-axis section prescription followed by baseline and stress tagging acquisitions. A segmented k-space technique with tagging pulses is used to acquire four to six short-axis sections with five to seven cardiac phases per section (single-section, multiphase mode) and one section per breath hold. A moderate NVS (7-13) and k1 are used depending on the heart rate. One "dummy" radio-frequency excitation is used per section to drive spoiled GRE signal to equilibrium, and two orthogonal tagging projections are obtained per short-axis section to permit 2D stress analysis from orthogonal tagging patterns. Both orthogonal tag projections for each short-axis section are obtained in the same breath hold. After each breath hold, the patient relaxes for approximately 30 seconds before the next section is acquired during the next breath hold. Similar to the protocol in standard stress echocardiography studies, the patient is limited to 15 minutes of dobutamine administration. Long-axis sections yield tagging data for computation of 3D strain measurements.
CONCLUSIONS
A “one-stop shop” for evaluation of cardiac disease with MR imaging is progressing toward clinical reality and promises to have a major effect on care of patients with cardiac disease. T1-weighted conventional spin-echo imaging gated to the cardiac cycle yields good anatomic detail but requires long imaging times and provides only static images of a single cardiac phase. Fast MR imaging with ECG-gated, low-flip-angle, segmented k-space GRE sequences provides excellent image quality with sufficiently high temporal resolution to “freeze” cardiac motion. Segmented k-space sequences improve on standard ECG-gated GRE sequences by imaging many cardiac phases, or frames of a cine sequence, in a single breath hold with prospective cardiac gating. As commercial implementations of segmented k-space imaging become more widely available, the applications of this technique are expanding from research protocols to include many clinical applications in the heart and great vessels. Such applications include evaluation of vascular anatomy (coronary angiography, aortic disease, aberrant vessels, vascular access), cardiac anatomy (congenital anomalies, right ventricular dysplasia, constrictive pericarditis, valvular function), myocardial perfusion, and myocardial wall motion.

REFERENCES


