Optimizing Cardiac MR Imaging: Practical Remedies for Artifacts

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With ongoing technical advances in magnetic resonance (MR) imaging, the clinical demand for cardiac MR evaluations has been increasing. Cardiac MR imaging techniques have evolved from traditional spin-echo sequences to breath-hold spoiled gradient-echo and balanced steady-state free precession sequences. The most recently developed techniques allow evaluation of myocardial function, perfusion, and viability; coronary angiography; flow quantification; and standard morphologic assessments. However, even with the most sophisticated acquisition techniques, artifacts commonly occur at cardiac MR imaging. Knowledge of the origin, imaging appearance, and significance of these artifacts is essential to avoid misinterpreting them as true lesions. Some artifacts are caused by simple errors in positioning of the patient, coil, or electrocardiographic leads; radiofrequency interference from nearby electronic equipment; or metallic objects within the magnetic field. Others are directly related to a specific MR imaging sequence or technique. Accelerated imaging techniques such as parallel imaging, which are used to shorten acquisition and breath-hold times in cardiac evaluations, are particularly vulnerable to artifacts. If an artifact severely degrades image quality, the acquisition should be repeated with appropriate adjustments to decrease or eliminate the problem.

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Abbreviations: ECG = electrocardiographic, FOV = field of view, GRAPPA = generalized autocalibrating partially parallel acquisition, GRE = gradient echo, RF = radiofrequency, SE = spin echo, SENSE = sensitivity encoding, SNR = signal-to-noise ratio, SSFP = steady-state free precession, TE = echo time, TI = inversion time, TR = repetition time

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Introduction

With recent technologic advances in magnetic resonance (MR) imaging hardware and software, many techniques now are available for cardiac MR imaging. Recently developed techniques have expanded the clinical applications for cardiac MR imaging to include assessments of myocardial function, perfusion, and viability; flow quantification; and coronary angiography (1–9). Good image quality is the primary requisite for accurate interpretation of cardiac MR images. However, even if images are obtained by well-trained staff using sophisticated techniques, it is impossible to eliminate every artifact from MR images. In addition to ghosting, geometric distortion, and ripple artifacts, which are familiar to radiologists who regularly perform MR imaging, many other kinds of artifacts may occur at cardiac MR imaging that are specific to the modality or the acquisition technique (Table). Moreover, new types of artifacts emerge regularly as new imaging techniques are developed (10). To avoid misinterpreting an artifact as a true lesion, it is essential to be familiar with the various artifacts that may appear at cardiac MR imaging and to understand their effects on the quality of imaging data. In the case of severe artifacts, it is also important to know how to avoid or minimize the problem. The article provides an overview of artifacts that may be seen in cardiac MR imaging and offers practical remedies for eliminating or mitigating them.

Patient Preparation and Positioning

Various measures may be taken before or during image acquisition to avoid or mitigate artifacts. First, the importance of breath holding should be explained to the patient before the imaging examination. Image acquisition at end expiration is preferred because it is more reproducible (11).

Second, because almost all cardiac sequences are gated to the patient’s cardiac cycle, electrocardiographic (ECG) leads should be applied and the ECG waveform evaluated before image acquisition is begun. A tracing that has poor amplitude requires lead repositioning. However, even with optimal lead placement, magnetohydrodynamic effects from flowing ions in the magnetic field (especially at high field strengths such as 3.0 T) and gradient switching noise may degrade tracings after the patient is placed within the magnet. The use of vectorcardiography may help improve the quality of gating (12).

Third, the placement of surface coils in relation to the heart is very important. The preferred coils for cardiac imaging are dedicated cardiac coils and dedicated torso array coils. In order to achieve a good signal-to-noise ratio (SNR), the center of both the anterior and the posterior surface coils should be well aligned with the center of the heart (Fig 1). Furthermore, since the homogeneity of the magnetic field decreases with increasing distance from the magnet isocen-
After the patient is positioned within the magnet, multiplanar scout images should be obtained and reviewed to ensure that the surface coils are properly positioned over the heart and that the patient is positioned so that the heart is at or near the magnet isocenter. Sagittal images are the most useful for verifying the surface coil position (Fig 1c). It is also important to recheck all coil power connections before beginning the image acquisition. Excessive noise on an image could be due to the unintended disconnection of a coil from the power source (Fig 2).
Two cine MR imaging techniques are commonly used to assess cardiac function: the segmented-k-space spoiled gradient-echo (GRE) sequence and the balanced SSFP sequence. Balanced SSFP sequences provide better SNR, increased contrast between myocardium and blood, and, thus, greatly improved image quality in comparison with those obtainable with spoiled GRE sequences. Image acquisition with spoiled GRE sequences takes less time than that with balanced SSFP sequences applied at the same bandwidth; however, to achieve a good SNR at spoiled GRE imaging, a lower-frequency bandwidth typically is needed. Therefore, SSFP acquisitions may take less time than spoiled GRE acquisitions when standard settings are used.

In segmented approaches to image data acquisition, only a fraction of the total number of k-space lines is acquired during one heartbeat.
Typically, a breath hold that lasts 10–12 cardiac cycles is required to obtain all the k-space lines needed to fill the image matrix. Because of variations in the cardiac cycle over time, ECG gating is necessary.

In retrospective gating, which is the most commonly used method, the data for a given section are acquired continuously throughout the cardiac cycle and are time-stamped to allow their assignment to the proper segment of the cycle. Data from several different cardiac cycles are combined to yield a single cine sequence. Because a single acquisition spans multiple heartbeats, all segments of the cardiac cycle are included. However, the patient’s heart rate and rhythm must be regular to produce high-quality images; irregularities in the cardiac cycle cause cine images to appear blurred. Most vendors incorporate arrhythmia rejection in their cine sequences, often by excluding cycles in which the R-R interval differs from a preset range of acceptable values. However, this method requires increased acquisition and breath-hold time, and therefore it is an imperfect solution. In patients with highly variable R-R intervals, prospective gating may be necessary.

In prospective gating, the onset of the R wave triggers the image data acquisition. To compensate for physiologic variations in heart rate, the acquisition window is usually 10%–20% shorter than the average R-R interval. Unfortunately, this means that the end of the cardiac cycle (late diastole, which often includes atrial contraction) is excluded from the image acquisition; thus, this method is not the first choice for evaluating diastolic function (including valvular flow), although it is suitable for use in evaluating systolic function. One potential advantage of prospective gating over retrospective gating is that it is less sensitive to variations in the duration of diastole such as those seen in patients with sinus arrhythmia and in some with atrial fibrillation (Fig 5).

In patients who cannot hold their breath for the duration of a segmented acquisition or in whom the ECG signal is weak, a single-shot technique may be used. With recent developments in gradient hardware, a repetition time (TR) of less than 3 msec is achievable with balanced SSFP MR imaging. The balanced SSFP sequence is now preferred for real-time functional imaging because it provides a high SNR even with a short TR (15,16). One entire cardiac cycle (one R-R interval), in one section location, is acquired at a time. The number of phases acquired per cardiac cycle depends on the heart rate and the usual tradeoff between spatial and temporal resolution. Although gating is not necessary for real-time imaging, when possible, prospective gating often is used to allow the synchronization of cine images from multiple section locations for viewing as movie clips (15). Real-time imaging may be

Figure 5. Cine cardiac MR images obtained with retrospective (a) and prospective (b) gating in a patient with atrial fibrillation and an irregular heartbeat show improved image quality in b, an image reconstructed from a data set that omitted end-diastolic information.
Balanced SSFP imaging is useful for evaluating the cardiac anatomy and function but has limited value for tissue characterization based on signal intensity. A typical feature of balanced SSFP sequences is the very high signal intensities of both fluid and fat, which have completely different T1 and T2 values but similar T2/T1 ratios. Blood inflow or motion effects may further modify the contrast obtained with balanced SSFP sequences (19).

Balanced SSFP sequences initially had only limited application because of the high prevalence of banding artifacts on the resultant images. Banding (or dark band) artifacts are caused by the dephasing of spins with resultant loss of the steady-state signal during a single TR (19–24). These artifacts appear predominantly at off-resonance points in the magnetic field (Fig 7a) or wherever there is a significant disruption of field homogeneity. Therefore, banding artifacts are worsened by (a) a longer TR, (b) an off-resonance RF pulse (which occurs when the frequency of the RF synthesizer on the MR imaging system is different from the local precession frequency of magnetization), and (c) a significant field inhomogeneity.

On balanced SSFP images, the dark striplike bands generally appear in stationary tissues at the edges of the field of view (FOV), where the
magnetic field is least uniform (Fig 7b). Such artifacts may not be visible in the myocardium and lungs because these tissues have low signal intensity on balanced SSFP images; the artifacts tend to be seen more often in high-signal-intensity areas (eg, blood and fat). However, they also may appear along the inferolateral wall of the left ventricle.

Figure 7. (a) Graph shows the steady-state signal amplitude achieved with a balanced SSFP sequence as a function of dephasing between pulses. The signal profile may be described as a plateau that is interrupted regularly by sharp decreases in amplitude near odd multiples of π radians or when the center frequency offset is larger. These off-resonance points produce dark band artifacts like those shown on the short-axis breath-hold SSFP cine images in b–e. (b, c) Dark band artifacts (arrows) are obvious in the high-signal-intensity stationary tissues near the edge of the FOV in b and in the inferolateral wall of the left ventricle in c. Such artifacts are less commonly seen in the lung and myocardium because these tissues have low signal intensity on SSFP images. (d) In another patient, a dark band flow artifact in the left ventricular cavity (arrow) has an irregular appearance because of the forward motion of the in-plane flow. (e) Image at the base of the heart in a third patient shows severe flow-related artifacts (arrow) caused by spins moving out of the plane of imaging near the position of a dark band artifact.
Teaching Point

homogeneity. A volume shim centered on the left
be given to shimming to maximize the main field
(particularly at 3.0 T), increased attention must
TR is limited by the specific absorption rate
asymmetric readout as well as reduced spatial
SNR. Other methods to decrease the TR include
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SNR. Other methods to decrease the TR include
asymmetric readout as well as reduced spatial
resolution. Second, since the ability to minimize
TR is limited by the specific absorption rate
(particularly at 3.0 T), increased attention must
be given to shimming to maximize the main field
homogeneity. A volume shim centered on the left
ventricle works best. During shimming, it is help-
ful to ask the patient to breathe shallowly so as to
minimize chest motion. Third, if dark band arti-
facts are not fully suppressed after shimming, the
center frequency should be aligned more closely
with the water resonance frequency. This can be
done manually or by acquiring a frequency-shift
scout image series (Fig 8). Adjusting the center
frequency will cause the dark bands to shift in
location (25).

Parallel Imaging

Fast imaging with high temporal and spatial reso-
lution is of great importance in most cardiac MR
imaging applications (26–28). Parallel imaging
methods may help accelerate image acquisition,
but at the costs of reduced SNR and increased
artifacts. In general, the SNR is reduced by at
least the square root of the acceleration factor. In
its most common application at 1.5 T, an ac-
celeration factor of two is used. An additional
decrease in SNR may be expected, with the size
of the decrease depending on the geometry factor
of the underlying coil array (27).

Various reconstruction algorithms have been
developed for parallel imaging, including si-
multaneous acquisition of spatial harmonics, or
SMASH (26); sensitivity encoding (SENSE)

Figure 8. Frequency-shift technique. Balanced SSFP scout image series obtained with a 3.0-T mag-
net and with progressive increases in frequency (from −40 Hz to 160 Hz) shows gradual shifts in the
position of a dark band flow artifact across the heart until the left ventricle is unobstructed.
techniques decreases the RF deposition required to generate an image by an amount approximating the acceleration factor, while the strong signal at 3.0 T allows a substantial acceleration of image acquisition with maintenance of a sufficient SNR (31–33). However, these accelerated acquisitions are prone to artifacts.

A residual aliasing artifact specific to SENSE imaging has been described (34). The characteristic “wraparound” artifact occurs when the reconstructed FOV is smaller than the object imaged (Fig 9). SENSE imaging does not allow the “unwrapping” of the overlapped image data. Unlike the aliasing artifacts that occur at conventional (nonparallel) imaging, these artifacts appear not only at the edges of the FOV but also at its center. To remove these aliasing artifacts, the size of the FOV may be increased; however, this solution results in decreased spatial resolution.

The location of the SENSE artifact depends on the SENSE factor; the artifact moves closer to the edge of the image as the SENSE factor is reduced (34). GRAPPA offers an advantage over SENSE when the FOV is smaller than the
imaging is most commonly performed after the administration of a gadolinium-based contrast material (0.05–0.1 mmol gadolinium per kilogram of body weight) at a rate of 3–5 mL/sec, followed by a saline flush (30–40 mL) administered at the same rate.

The MR imaging techniques most commonly used for evaluation of myocardial perfusion are spoiled GRE sequences with or without the incorporation of hybrid echo-planar techniques to increase imaging speed (7,8). Short echo time (TE), short TR, and magnetization preparation pulses are commonly used to increase T1 contrast in the myocardial region. Standard magnetization preparation includes section-selective or non-selective 90° saturation-recovery pulses (8,39). Alternative techniques such as balanced SSFP sequences may help improve SNR at perfusion imaging (40,41). Three to five image sections may be acquired over 40–60 heartbeats, depending on the duration of the R-R interval. The temporal resolution for perfusion imaging is typically one cardiac cycle (R-R interval) or, in patients with tachycardia, every other R-R interval. Parallel imaging methods may be incorporated to further decrease the acquisition time (increase the number of sections acquired per R-R interval).

Although research studies often emphasize quantitative analysis, a simple visual assessment is the most common approach used to interpret first-pass perfusion images in the clinical setting.
Regardless of their cause, the artifacts are ameliorated by higher spatial resolution. Parallel acquisition schemes are the most efficient way to improve both temporal and spatial resolution (45). The greater SNR available with 3.0-T magnets may help offset the loss in SNR that results from incorporating parallel acquisition techniques. In addition, lower concentrations of gadolinium may be used at 3.0 T, leading to less severe magnetic susceptibility effects (46,47).

**Aliasing Artifacts.**—Aliasing artifacts are common in first-pass perfusion imaging and may be especially pronounced when parallel imaging techniques are used. As mentioned earlier, care must be taken to select a sufficiently large FOV (Fig 12). Rotation of the imaging plane to match the patient’s chest wall anatomy may allow the use of a smaller FOV without resultant aliasing effects. It is extremely important to instruct the patient about the breath holding procedure before image acquisition is begun. Breath holding is especially vital as the contrast medium transits the left ventricular myocardium.
Delayed Contrast-enhanced (Viability) Imaging
The results of a number of studies have demonstrated the effectiveness of a segmented inversion-recovery spoiled GRE sequence for...
diagnosing the presence, location, and transmural extent of acute and chronic myocardial infarction (48–51). To minimize cardiac motion, image acquisition is performed in mid diastole by instituting a specified delay after the R wave on the ECG tracing. The magnetization of the heart is then prepared with a nonselective 180° inversion pulse to increase T1 weighting (51). The inversion time (TI) is defined as the time between this 180° pulse and the acquisition of the central lines (central k-space segment). With the segmented k-space approach, 23 lines of k-space are acquired in each data acquisition window, during every other heartbeat. Typically, a breath-hold duration of eight to 10 cardiac cycles is required to fill the image matrix.

**Artifacts Due to Incorrect TI.**—Selecting the appropriate TI is extremely important for obtaining accurate images (Fig 14). The TI to null the signal from normal myocardium varies from 200 to 350 msec, depending on the contrast agent dose and the delay between the injection of the agent and the initiation of image acquisition, as well as on the patient’s physiologic characteristics (cardiac output, renal clearance of gadolinium, and body weight). The TI selected should be the time when the signal intensity difference between infarcted and normal myocardial tissue is at its maximum, or immediately after (Fig 14c). If the TI is too short, the signal from normal myocardium will be below the zero crossover point, and the normal myocardial tissue will have a negative magnetization vector at the time of k-space data acquisition (52). Since signal intensity corresponds to the magnitude of the magnetization vector, the signal intensity of normal myocardium increases as the TI becomes shorter, whereas the signal intensity of infarcted myocardial tissue decreases until it reaches the zero crossover point (Fig 14b). At this point, the signal in infarcted myocardium is null, and that in normal myocardium is hyperintense. In the opposite extreme, if the TI is too long, the magnetization of normal myocardium will be above zero and the normal tissue will appear gray instead of black. In principle, the optimal TI, at which the signal in normal myocardium is null (the so-called null time), must be determined by imaging iteratively with different TI values. To determine the optimal TI, a TI scout sequence may be applied (51). Experienced operators usually can determine the

![Figure 14.](image-url)
polarity artifacts over a relatively wide range of null times (Fig 15) (53,54). This reconstruction technique may be especially useful for radiologists who have little experience in selecting the appropriate TI. However, the TI selected should still be as close as possible to the optimal value to maximize the SNR and contrast-to-noise ratio.

**Effects of Suboptimal Delay at Contrast-enhanced Imaging.**—Viability imaging is usually performed 10–20 minutes after the intravenous injection of a gadolinium-based contrast material (0.1–0.2 mmol/kg gadolinium) (55). The results of recent studies (9,49,51) suggest that when an appropriate TI is selected, the size of hyperenhanced regions does not change if imaging is per-

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**Figure 15.** Magnitude (top row) and phase-sensitive (bottom row) cardiac MR images obtained with a segmented inversion-recovery spoiled GRE sequence in a normal subject with a 3.0-T magnet at TI of 200 msec (left column), 300 msec (middle column), and 350 msec (right column). On the magnitude images, the signal intensity of myocardium is high on the image obtained with the shortest TI (top left); mixed (mottled appearance) on the image obtained with the intermediate TI (top middle); and null on the image obtained with the longest TI (top right). The corresponding phase-sensitive images show relatively null signal in myocardium regardless of TI.
Imaging after a shorter delay, especially when higher initial doses of gadolinium are used, may lead to difficulty in differentiating the signal of the left ventricular cavity from that of the hyper-enhanced myocardium.

**B. Field Inhomogeneity Artifacts.**—The use of standard inversion-recovery pulses may result in inhomogeneous signal suppression in normal myocardium and, thus, a false diagnosis of myocardial disease. This phenomenon is especially pronounced at 3.0 T because of the higher $B_1$ field inhomogeneity of the transmit coils as a result of the interaction of the $B_1$ field with the body (Fig 16). However, this field inhomogeneity effect often may be reduced by using an adiabatic inversion preparation pulse (56).

**Motion-related Ghost Artifacts.**—Ghost artifacts due to motion are one of the most common reasons for poor quality of cardiac MR images. Breath holding and ECG gating are usually sufficient to account for these motions during a typical image acquisition time of 8–10 seconds for the two-dimensional version of the segmented inversion-recovery spoiled GRE sequence. Unfortunately, breath holding may be poor and gating inadequate. The segmented nature of the sequence, along with differences in heart position between cardiac cycles, then may lead to motion-induced artifacts (Figs 17, 18).
decrease the number of k-space lines required to complete the image matrix, resulting in faster imaging with no loss in spatial resolution. Occasionally, imaging with only the anterior coil elements (keeping the posterior coils turned off) allows a smaller FOV phase than expected without producing a wraparound artifact over the heart. Another strategy to reduce the breath-hold duration is to increase the number of k-space lines acquired per cardiac cycle, although this results in a reduction in temporal resolution.

In some patients, even with the use of the techniques described earlier, breath holding is inadequate. In this situation, single-shot acquisition techniques may be useful (57). Although there is a reduction in spatial and temporal resolution with single-shot methods, in our experience the inversion recovery–prepared method (single-shot inversion-recovery SSFP) provides reasonable image quality. Compared with the single-shot inversion-recovery spoiled GRE technique, the inversion-recovery SSFP sequence typically allows high-bandwidth imaging (short TE and TR for faster imaging) with good preservation of SNR. Clinical benefits of using this technique are patient comfort, faster imaging, and decrease or elimination of breathing-related artifacts (Fig 19). However, since the inversion-recovery SSFP sequence is typically T2 or T1 weighted, there may be a reduction in the pure T1 contrast effects that normally follow contrast medium adminis-

Figure 18.  (a, b) Delayed contrast-enhanced MR images show motion-induced ghosts of the heart and chest wall, artifacts of poor breath holding (a), and a ghost of the heart alone (b), an artifact caused by defective ECG gating. (c) Delayed contrast-enhanced image obtained with adequate breath holding and ECG gating shows no artifacts.
performed during every third heartbeat (gating factor of three) rather than every other heartbeat (gating factor of two) to allow sufficient time for the recovery of magnetization between successive inversion pulses. Incomplete relaxation results in the reduction of the signal intensity difference between infarcted and normal myocardium and may lead to TI shortening with a resultant delay in the nulling of signal in normal myocardium. Because of the latter effect, when the gating factor is increased, the TI to null normal myocardium often must be increased (by 20–40 msec). In patients with bradycardia, triggering with every heartbeat might still allow adequate time for magnetization recovery, while resulting in a 50% reduction in the breath-hold time. Alternatively, or in addition, the number of k-space lines acquired per cardiac cycle may be increased.

Ghost Artifacts from Long T1.—Ghost artifacts also may result from regions within the FOV that have long T1 values (such as cerebrospinal fluid or pericardial effusion). This phenomenon is due to the fact that with long T1, the train of inversion pulses in the segmented inversion-recovery spoiled GRE sequence leads to the

Figure 19. (a) Standard segmented inversion-recovery spoiled GRE image obtained in a patient who had difficulty in holding his breath shows a severe respiratory motion-related artifact. (b) Short-axis ECG-gated non–breath-hold image from a multisection acquisition obtained with a single-shot inversion-recovery SSFP sequence at the same level as a demonstrates a significantly improved appearance.

Adjustments of the imaging parameters are often required in patients who have tachycardia or bradycardia. Because of the shorter mid-diastolic period in patients with tachycardia, the number of k-space lines acquired in every cardiac cycle should be reduced to minimize blurring from cardiac motion. In addition, imaging should be
An artifact can be reduced by applying a single additional nonselective inversion pulse approximately 2000 msec (the time it takes for the transudate to reach the zero crossover point after the application of an inversion pulse) before the initial 180° inversion pulse of the inversion-recovery sequence. This will result in the suppression of signal from the pericardial effusion (which has a long T1) while maintaining signal in the myocardium (which has a short T1 in the presence of gadolinium). Since such ghost artifacts may be mistaken for myocardial hyperenhancement, the interpreter should be wary of a hyperenhancement pattern that is not in a typical coronary artery distribution. In general, hyperenhanced regions should be verified by acquiring images in at least two orthogonal planes. A fast alternative acquisition method is a phase-sensitive inversion-recovery sequence in which the signal from long T1 oscillation of magnetization before each group of k-space acquisitions (Fig 20). The effect is a ghost artifact that appears in the phase-encoding direction (Fig 21). Ghost artifacts often can be moved outside the region of interest by swapping the frequency-encoding and phase-encoding directions or by using in-plane rotation during image acquisition. However, the applicability of this solution depends on the skill of the operator in immediately identifying the artifact during the image acquisition and on the patient’s ability to perform the additional breath holds needed to repeat the acquisition.

For artifacts caused by cerebrospinal fluid and pericardial effusion, a simple solution is to place a saturation slab over the spinal canal or the area of effusion. In a case of pericardial effusion, the artifact can be reduced by applying a single additional nonselective inversion pulse approximately 2000 msec (the time it takes for the transudate to reach the zero crossover point after the application of an inversion pulse) before the initial 180° inversion pulse of the inversion-recovery sequence. This will result in the suppression of signal from the pericardial effusion (which has a long T1) while maintaining signal in the myocardium (which has a short T1 in the presence of gadolinium). Since such ghost artifacts may be mistaken for myocardial hyperenhancement, the interpreter should be wary of a hyperenhancement pattern that is not in a typical coronary artery distribution. In general, hyperenhanced regions should be verified by acquiring images in at least two orthogonal planes. A fast alternative acquisition method is a phase-sensitive inversion-recovery sequence in which the signal from long T1...
determine whether such a feature is artifactual, the acquisition should be repeated with reduced section thickness, a fat suppression technique, or orthogonal views. We do not recommend fat suppression routinely, since high signal intensity in epicardial fat actually may help distinguish between the epicardial border of nulled myocardium and the lung fields, which also have low signal intensity. However, when fat suppression is applied, the k-space lines must be acquired in a centric fashion. With linear acquisition, fat, by virtue of its short T1, will have recovered its signal by the time the central lines of k-space are acquired, negating the attempt at fat suppression.

**Velocity-encoded MR Imaging of Flow**

A commonly used MR technique to evaluate blood flow is phase-contrast or velocity-encoded MR imaging (59–61). Gradients may be varied in amplitude or duration to sensitize the pulse sequence to fast or slow flow. The operator selects the maximum velocity to be encoded by the sequence. Depending on the sequences available, phase-contrast measurement can be performed in a breath hold or during normal respiration by using prospective or retrospective cardiac gating. Both magnitude and phase images are often reviewed.

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**Figure 22.** (a) Short-axis delayed contrast-enhanced MR image of the left heart base shows a subendocardial high-signal-intensity band along the anterolateral wall of myocardium (arrow), an effect of partial-volume averaging of blood with endocardial trabeculae. (b) Long-axis view of the left ventricle shows normal myocardium with a partial-volume averaging effect (arrow) near the base, where the myocardial border is obliquely oriented in relation to the imaging section. (c) Short-axis balanced SSFP cine image shows a similar volume averaging artifact (arrow).
Partial-Volume Averaging Effects.—Underestimation of flow and velocity may occur if the voxel selected is too large or if the vessel is not perpendicular to the plane of imaging (62). Too large a voxel size results in reduced measured velocities either because stationary tissues are included in the voxel or because intravoxel dephasing and saturation of slow in-plane flow are increased. Partial-volume averaging artifacts are most commonly seen in small and tortuous vessels. An easy way of decreasing the voxel size (smaller pixels) is to decrease the FOV as much as possible (Fig 24). Remember, a wraparound artifact does not significantly affect the precision of the measurements as long as it is not superposed on the vessel of interest. However, an optimal section thickness is required to achieve optimal SNR. A section thickness of 6–8 mm is optimal to minimize partial-volume averaging effects yet maintain the SNR. For small vessels, section thickness should be reduced to 5 mm. We prefer to obtain velocity measurements after the injection of a gadolinium-based contrast material to improve overall SNR. Often, vessels imaged in

Common errors in phase-contrast imaging are related to inappropriate maximum velocity encoding settings, imaging plane misalignment, partial-volume averaging, inadequate temporal or spatial resolution, and flow and phase offset errors (61).

Aliasing Artifacts.—Aliasing occurs when the maximum velocity sampled exceeds the upper limit imposed by the chosen velocity encoding setting, resulting in apparent velocity reversal. To avoid aliasing, the velocity threshold must be correctly selected. The maximum value selected should slightly exceed the expected velocities. Aliasing results in an artifactual reduction of the measured flow in direct proportion to the extent (severity) of the aliasing artifact. Fortunately, it is the easiest error to detect in flow measurements. It can be perceived on the velocity images, wherever the voxels of assumed peak velocities have an inverted signal intensity compared with that of surrounding voxels (Fig 23).
Figure 24. (a) Cross-sectional image from a three-dimensional MR angiographic data set acquired in a plane perpendicular to the right inferior pulmonary vein (arrow) shows an aliasing artifact. (b, c) Magnitude (b) and phase (c) images, reconstructed with a used for localization and with the smallest possible FOV so as to maximize the SNR, show the same artifact. Such artifacts do not significantly affect measurements of flow velocity unless they are superposed on the anatomy of interest.

an orthogonal plane have a circular appearance. However, ovoid contours may be found in veins or vascular prostheses (Fig 24). An ideal orthogonal view of the vessel or a cardiac valve can be obtained from two perpendicular images and be used as a localizing reference to prescribe the appropriate phase-contrast view.

Other Types of Artifacts.—Artifacts from vessel pulsation or cardiac and respiratory motions are common and may interfere with velocity estimates. Unstructured flow (ie, flow with a high Reynolds number) leads to intravoxel dephasing of the signal of flowing spins and causes poor phase-contrast measurements of velocity. This technique is also sensitive to eddy currents, which may occur in the tissue outside the vessel, causing phase shift and incorrect measurements (metal artifacts).

Morphologic Imaging
Pulse sequences currently used for morphologic evaluations can be generally divided into dark-blood and bright-blood techniques. When bright-blood techniques are used, flowing blood has high signal intensity. Bright-blood techniques are spoiled GRE or balanced SSFP sequences with segmented or single-shot k-space acquisitions. Image contrast when spoiled GRE sequences are used depends on inflow enhancement of blood; when balanced SSFP sequences are used, contrast depends on the steady-state signal of blood, as described earlier. In dark-blood or black-blood imaging techniques, fast-flowing blood appears black or has low signal intensity. Dark-blood techniques eliminate blood flow artifacts unless stagnation is present; therefore, they provide excellent depiction of the architecture of the walls of blood vessels and cardiac chambers. Examples of dark-blood techniques include conventional spin-echo (SE), breath-hold fast SE, single-shot fast SE with double inversion-recovery pulses to suppress the signal from blood (ie, inversion-recovery fast SE), spoiled GRE, and SSFP sequences. The single-shot inversion-recovery fast SE sequence is the most commonly used black-blood technique and can be implemented with
Figure 25. Diagram of a dark-blood imaging sequence shows the initial inversion of signal from all tissues with the application of a nonselective (NS) $180^\circ$ pulse in late diastole, followed by the restoration of signal in the selected section with the application of a section-selective (S) $180^\circ$ pulse. After a delay (TI), when the signal of flowing blood reaches its null point (in mid diastole), a series of fast SE pulses is applied. The blood signal null point varies with the R-R interval, and TI therefore is shorter in patients with a faster heart rate.

Figure 26. Short-axis cardiac MR images obtained with a dark-blood inversion-recovery fast SE sequence. (a) Image obtained with TR adjusted so that data were acquired in mid diastole provides a clear view of the cardiac chambers. (b) Image obtained with too long a TR shows blurring of the chamber walls because of a partial recovery of the signal in blood, an effect that also may be seen on contrast-enhanced images. (c) Image obtained with too short a TR shows blurring of the blood-myocardium interface because of base-apex contraction during systole and resultant misalignment of image data from the selective inversion pulse (during diastole) with data from the readout pulses (during systole).
or without breath holding (Fig 25) (63). Parallel imaging is performed to improve spatial and temporal resolution in patients with faster heart rates (32). Dark-blood imaging techniques are available in both T1- and T2-weighted variants as well as with and without fat suppression. Note that for T1-weighted variants, the effective TR should be less than 800 msec. For T2-weighted double inversion-recovery sequences, the TR should remain long and the acquisition window should cover two or three heartbeats.

The timing of data acquisition is critical for optimal results. To optimize dark-blood sequences, one should adjust the TR so that data are acquired in mid diastole in order to eliminate cardiac motion artifacts (Fig 25). If the TR is set too short, systolic motion reduces the myocardial signal and decreases contrast between the blood pool and myocardium. If the TR is too long, the blood signal begins to recover (Fig 26). Because of the T1 shortening effect of intravenously administered gadolinium-based contrast materials, it is necessary to obtain dark-blood images before administering the contrast agent.

Artifacts Caused by Ferromagnetic Materials

Metallic materials are widely used in arterial stents, clips placed during bypass surgery, and prosthetic cardiac valves (64). Artifacts induced by a metallic implant may disrupt the diagnostic capabilities of MR imaging (Fig 27). Generally, two types of metal-induced artifacts may arise: (a) magnetic susceptibility artifacts, which arise from local field inhomogeneities caused by the presence of ferromagnetic materials within the magnet, and (b) RF artifacts, which are due to
decreased signal intensity around metallic parts (Fig 27). As a result of partial-volume averaging, these artifacts may appear in normal tissue and be mistaken for a pathologic condition (Fig 28).

The severity of susceptibility artifacts in general depends on the pulse sequence used, the magnetic susceptibility of the metal, the orientation of the metallic implant with respect to the deterioration of excitation and refocusing RF pulses caused by the induction of eddy currents in metallic implants (64,65). MR imaging artifacts caused by magnetic susceptibility and RF effects appear as bands with increased or
direction of the main magnetic field and the readout direction, the imaging bandwidth, and the strength of the main magnetic field. Magnetic susceptibility leads to two distinct but related artifacts: 

(a) signal loss from $T_2^*$ decay and (b) distortion in the readout direction, particularly at low-frequency bandwidths. RF eddy current artifacts are also dependent on geometry, orientation, and the material of the metallic implant (65,66). In the presence of ferromagnetic materials, magnetic susceptibility artifacts are the major cause of signal loss. With conductive but nonferromagnetic materials such as copper, RF artifacts are more common. Both types of artifacts are more pronounced at 3.0 T.

The artifacts on GRE images differ in appearance from those on SE images. The $180^\circ$ refocusing pulses in SE sequences compensate for intravoxel dephasing caused by static field inhomogeneities. The influence of $TE$ on the severity of susceptibility artifacts is much greater in GRE imaging than it is in SE imaging. In balanced SSFP imaging, factors that disrupt the steady state, such as magnetic susceptibility variations, result in off-resonance artifacts (Fig 29).

**Summary**

The continued development of the field of cardiac MR imaging has been paralleled by increased applications. However, each new application (viability and perfusion imaging, cine studies, flow and gradient measurement) is vulnerable to artifacts that may undermine the diagnostic value of the images. Knowledge about the causes and appearances of these artifacts is essential in order to avoid misinterpreting them as true lesions. In addition, those who perform cardiac MR imaging studies should be familiar with the available methods for eliminating artifacts or at least lessening their severity.

**References**


Optimizing Cardiac MR Imaging: Practical Remedies for Artifacts
Farhood Saremi, MD, et al

Because dark band artifacts are related to inhomogeneities in the magnetic field or center frequency offsets, they may be substantially reduced by reshimming and retuning of the imaging system.

Parallel imaging methods may help accelerate image acquisition, but at the costs of reduced SNR and increased artifacts.

Dark subendocardial rim artifacts are common in perfusion studies and may be confused with myocardial perfusion defects.

Selecting the appropriate TI is extremely important for obtaining accurate images.

Aliasing results in an artifactual reduction of the measured flow in direct proportion to the extent (severity) of the aliasing artifact.