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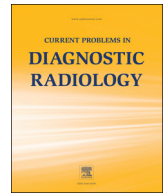
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Artifacts Affecting Musculoskeletal Magnetic Resonance Imaging: Their Origins and Solutions



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Among articles within the radiology literature, few present the manifestations of magnetic resonance imaging artifacts in a clinically oriented manner. Recognizing such artifacts is imperative given the increasing clinical use of magnetic resonance imaging and the emphasis by the American Board of Radiology on practical physics applications. The purpose of this article is to present magnetic resonance physics principles visually and conceptually in the context of common musculoskeletal radiology artifacts and their solutions, described using nonmathematical explanations.

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Introduction

Among articles within the radiology literature, few present the manifestations of magnetic resonance imaging (MRI) artifacts in a practical and clinically oriented manner. Recognizing such artifacts is imperative given the increasing clinical use of MRI and the simultaneous emphasis by the American Board of Radiology on practical physics applications for licensure certification. Thus, this article offers a pictorial compilation of musculoskeletal radiology MR artifacts, yielding a visual, in addition to conceptual, explanation of underlying physics principles. The artifact etiologies are briefly described, diagnostic pitfalls addressed, and possible technical remedies offered. The imaging artifacts are separated into those involving the subject (patient), those from the machine electronics, and those from data processing errors.

Before discussing artifacts, let us briefly review the basics of image creation. MRI is founded on the intrinsic magnetism of hydrogen in tissue. When placed in the external magnetic field of an MRI scanner, the spinning hydrogen protons precess about the direction of the magnetic field similar to the way a spinning top precesses about the direction of a gravitational field. The frequency of spin precession is directly proportional to the strength of the magnetic field.

The protons tend to polarize in the direction of the main magnetic field, forming a net magnetization that may be manipulated to create images. A radiofrequency (RF) pulse is used to induce a secondary magnetic field that alters the orientation of the net magnetization's precession. Some or all of the net magnetization is then oriented perpendicular to the main magnetic field,

which generates an oscillating magnetic field that may be detected in nearby RF coils. The strength of the subsequent MRI signal induced in the RF coil is dependent on the magnitude of the net magnetization and other factors. The rate at which this signal is lost (relaxation) depends on the protons' interactions with their local environment, which can be manipulated to distinguish different tissue types.

The induced electrical signal can be spatially encoded to permit image generation of a particular volume of anatomy, referred to either as a slice or plane of section. Linear magnetic field gradients are applied across the patient prior to signal detection, such that the magnetic field steadily changes across the field of view (FOV) of the patient. This yields spatially localized proton frequency and phase,¹ creating spatial positioning that is encoded in the signal induced in the RF coil. Mathematical transformations can accurately turn the induced signal into an image, as long as the frequency and phase correctly correspond to position. Many artifacts occur when this precise coordination is disrupted, upsetting the expected signal magnitude, relaxation timing, or precession phase, resulting in a misrepresentation of the location or tissue characteristics.

Subject-Related Artifacts

For the purposes of this article, common *subject-related* artifacts would be grouped into those caused by patient motion, voluntary and involuntary, and artifacts caused by foreign bodies implanted within the patient.

Macro-Motion

Subject motion is often visually recognized along the phase-encoding axis.² One reason for this is that acquisition of phase-

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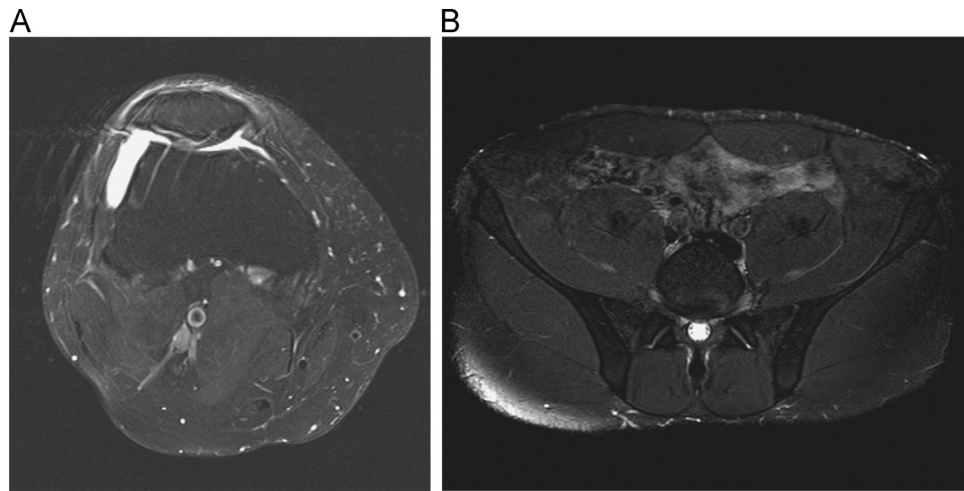


Fig. 1. (A) Motion artifact: Axial T2-weighted image with fat saturation demonstrating motion artifact causing both anatomic blur and repeated ghost images of the small knee effusion replicated across the phase-encoding direction from patient fidgeting. (B) Bowel-related physiologic motion artifact: Axial T2-weighted image with fat saturation demonstrates aphysic physiologic gastrointestinal motion causing anatomic blur.

encoding data is comparably slower than the acquisition of frequency-encoding information, making the phase-encoding data more susceptible to motion degradation.^{2,3} However, motion can effect data collection in any dimension depending on when the motion occurs during the image creation process. The resulting artifact is often recognizable as a series of duplicated “ghost” structures, or as a general blurring of the final image.^{3,4} Examples of motion range from patient fidgeting (Fig 1A) to involuntary physiologic motion of respiration, bowel activity (Fig 1B), and vascular pulsations (Fig 2). By its very nature, involuntary motion cannot be controlled; however, techniques can be used to minimize the effect of motion on the diagnostic quality of the final image.⁴

One remedy used to minimize macro-motion artifact is selecting faster imaging techniques that permit shorter imaging times, such as gradient echo and multi-shot or single-shot fast spin-echo techniques.^{3,4} Another approach is to utilize non-cartesian sampling. One technique, known as PROPELLER (GE), BLADE (Siemens), or MultiVane (Philips), samples signal in radial segments, rotating the radial segment between acquisitions like the blades of an airplane propeller.⁵ Although this increases overall acquisition time, this technique repeatedly fills “central” data, yielding redundant information.³ This oversampling of information decreases the

effect of motion’s effect on a single acquisition, enabling the degraded data to be excluded or corrected algorithmically.^{3,5} However, this advantage comes at the expense of lower image spatial resolution because of under-sampling, and streaking artifacts associated with radial MRI. This occurs secondary to under-filling of peripheral k-space, with k-space being the matrix in which acquired data from the digitized MR signals are stored.^{4,5}

Pulsation

If a pulsating vessel is imaged axially, the pulsating structure may result in a series of displaced “ghost” replicas of the primary vessel in the phase-encoding direction (Fig 2A). These circular phantom vessels may be mistaken for lesions or areas of marrow edema if the observer fails to recognize them as artifact.⁵ One option used in the setting of this pulsation is to switch the frequency and phase-encoding directions.^{2,5} Rather than mask the artifact, this displaces the artifact to a different region of the image, allowing a differentiation between artifact and true pathology (Fig 2B and C). This latter technique is particularly useful when the motion artifact projects over a specific region of interest on the original image. Alternatively, an additional saturation pulse can be applied to the anatomy just above or below the area to be

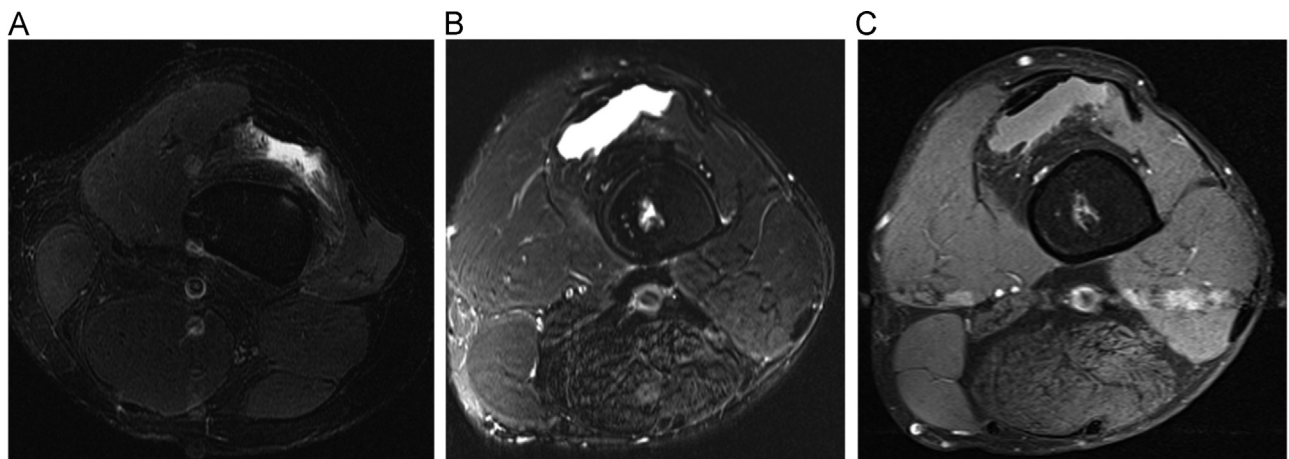


Fig. 2. (A) Pulsation artifact: axial T2-weighted image with fat saturation demonstrating pulsation artifact seen as multiple “ghost” replicas of the popliteal artery. (B) Pulsation artifact: axial T2-weighted image with fat saturation with pulsation artifact repeating along the phase-encoding direction, partially obscuring a T2 bright enchondroma centered within the femoral diaphysis. (C) Pulsation artifact: demonstrates the appearance of the image after switching the phase and frequency-encoding gradients to displace the artifact away the enchondroma.

imaged to null signal from blood traveling from those regions into the plane of interest.⁴

Magic Angle

Magic angle refers to focally increased signal in tissue fibers that are oriented at approximately 55° to the main magnetic field, and it is most often seen with short echo times.^{6,7} This occurs because T2 relaxation that normally causes diminished signal can be almost nonexistent when tissue is oriented at 55° relative to the main field.^{6,8} This causes hyperintensity due to accidental T2-weighting of signal in T1-weighted and proton density-weighted sequences.^{6,9} Most commonly this artifact is seen in rounded anatomic areas like joints, mimicking tendinosis, meniscal contusion, or neuritis, depending on the type of anatomy.⁷ Changing patient position is the most reliable method for artifact reduction.⁸ However, as this is not always feasible, correlations may be made with long echo-time sequences such as conventional T2 that have a sufficiently long TE to permit T2 decay and restoration of the expected tissue signal.^{6,7}

Chemical Shift

There are different types of chemical shift artifact. Although not typically regarded as a motion artifact, which causes phase misregistration, chemical shift occurs because of differences in proton spin frequency that lead to frequency misregistration at fat-water interfaces. The first type of chemical shift is the only type affecting conventional spin-echo imaging. The appearance may include a dark or bright band at fat-water interfaces.² These bands are caused by the fact that the hydrogen protons of water resonate faster than those of fat by approximately 220 Hz at 1.5 T.² This is problematic considering that images are created by applying a linear magnetic field gradient, which presupposes that the resultant proton precession frequencies change linearly across the FOV to generate accurate images. If any protons have precessional frequency variations that stem from a source other than the applied gradients, there would be mislocalization (eg, chemical shift) of the detected signal.¹⁰ Thus, the protons of hydrogen and water are artificially shifted because of their chemical shift (slight differences in frequency). Visually this creates dark or bright signal regions at the borders of water and fat (Fig 3).³

As this artifact is caused by differences in precession frequency between fat and water protons, it would be accentuated at higher magnetic field strengths that increase the differences in precession

frequency.⁶ There are several possible remedies; the first is to increase the gradient strength and subsequently the receiver bandwidth, thereby allocating a larger frequency range per pixel and minimizing the spatial range of the chemical shift.⁶ The same goal can be achieved by increasing the pixel size. However, the simplest solution is to use a fat saturation sequence.^{2,10}

A second type of chemical shift artifact is only encountered with gradient echo imaging, where differences in precession frequency between fat and water may be purposely manipulated through the selection of echo time (TE). If a TE is chosen where water and fat protons are “out of phase,” meaning that their average magnetization vectors are oriented in opposite directions, the resulting signal in that particular voxel is effectively canceled out, creating areas of signal void.⁵ Although this results in an unwanted dark band at the interface of fat and water in tissue, it can be used to create out-of-phase MRI to identify intracellular or microscopic fat.

Susceptibility

Fat and fluid interfaces are not the only substances responsible for misregistration artifacts; susceptibility effects from blood products, calculi, air, and small metal objects may result in misregistration, signal loss, and signal pile-up artifacts. Secondary magnetic fields are generated by the tendency, or “susceptibility,” of a given substance to become magnetized.³ These secondary fields cause local derangement of the main magnetic field, and the degree of derangement determines the extent of the subsequent susceptibility artifact.⁵ Most tissues are “diamagnetic,” and have a secondary field that opposes and detracts from the existing magnetic field. Other substances generate secondary fields that align with and add to the existing field, mildly for “paramagnetic” substances, and strongly for “ferromagnetic” substances.

The strength of secondary fields and the subsequent signal degradation created is influenced by the inherent difference between the magnetic susceptibility of adjacent structures.^{5,11} Because there is a large difference in magnetic susceptibility between native organ tissues and ferromagnetic metal implants (eg orthopedic hardware), the degree of local field disruption is significant, with ferromagnetic substances inducing strong secondary fields that cause undesirable variations in hydrogen proton spin precession frequency.^{5,11}

These precession frequency variations confound the expected linear variation caused by gradients. This leads to misregistration of the acquired signals, and various artifacts. Anatomic distortion,

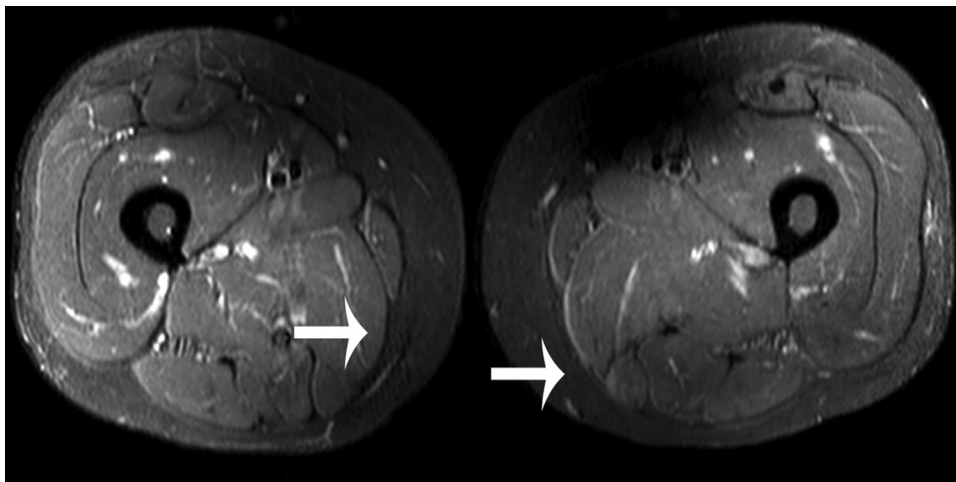


Fig. 3. Chemical shift artifact: axial T2-weighted image with fat saturation demonstrating chemical shift between adjacent water and fat protons resulting in bright and dark bands at the interface of these tissue types. Most notably in musculoskeletal imaging, this is seen between muscle and fat (white arrows).

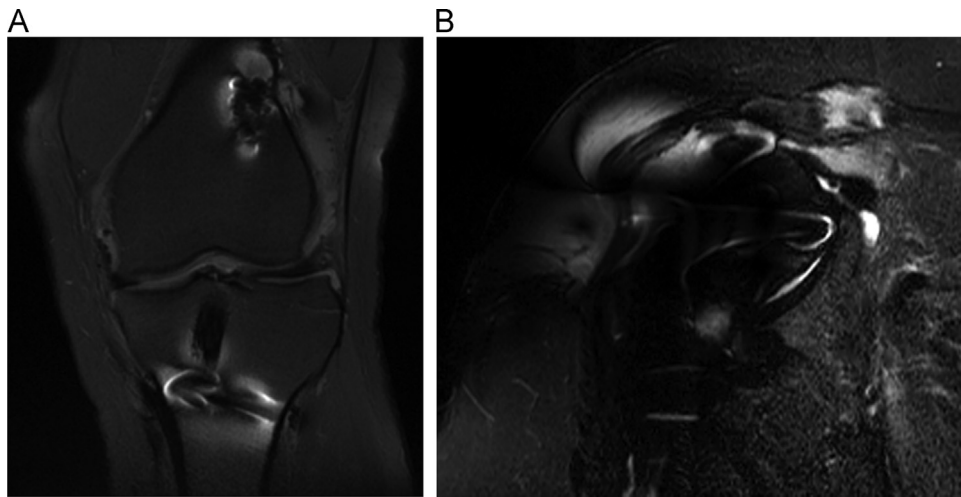


Fig. 4. (A) Metal artifact: coronal STIR of the knee with metal artifact from ACL fixation screws causing areas of dark signal void and bright signal pile-up. (B) Metal artifact: Coronal STIR of the shoulder with extensive local magnetic field disruption caused by cerclage wire resulting in large areas of signal void due to magnetic shielding by Eddy currents.

or “displacement artifacts,” may be seen along the frequency-encoding or the slice-selection direction because of these dimensions’ dependency on precession frequency.^{11,12} Bright regions where the displaced signal has accumulated and dark areas of signal void may also arise (Fig 4A).^{2,3,11} This local field disruption also disturbs any imaging application dependent on precise echo timing, such as some methods of fat saturation, where the result would be local failure of fat suppression.

The orientation of the hardware relative to the static magnetic field and the shape of the metallic component may also affect the severity of the artifact.^{9,13} Linear hardware such as stabilization rods or plates produce less field disruption than circular structures. Indeed, the degree of artifact can be slightly decreased by arranging the patient so that the long axis of the rod or plate is parallel to the main magnetic field. This rule is not as applicable to hardware with more complex shapes, such as the closed circular structure of a cerclage wire (Fig 4B). This is because Eddy currents can be induced in a ring, shielding the adjacent tissue from the effects of the RF pulse and causing a large void of signal seen as a black region.³

Susceptibility artifacts may be diagnostically useful. An example includes when hemorrhage is clinically suspected. Quick imaging techniques that tend to be more artifact-prone, such as gradient echo imaging, which lacks a refocusing pulse, are

purposely used in this setting to accentuate the artifact caused by hemosiderin. Although there is no perfect remedy for susceptibility artifacts, using fast spin-echo sequences featuring a refocusing pulse may partially correct for the signal displacement.⁹ Some institutions use a “metal-suppression” protocol that forgoes conventional fat suppression in patients with known metallic hardware, based on the expectation that such an application necessarily fails because of its reliance on an accurately prescribed range of suppressed spin frequencies.⁹ Instead, fat suppression is achieved using short tau inversion recovery techniques that are less influenced by the presence of magnetic field inhomogeneity.

Imaging techniques are becoming available that attempt to correct for both the signal loss and displacement caused by metal hardware.¹² Such sequences perform specialized acquisition techniques of larger datasets in an attempt to minimize these artifacts in images (Fig 5).¹² Although the details of such proprietary techniques are beyond the scope of this article, conventional measures that are routinely used include scanning on a 1.5 T rather than at 3 T magnet as variation in susceptibility necessarily be accentuated at higher magnetic fields. Broadening the readout bandwidth decreases the effect of field inhomogeneity at the cost of a slight loss in overall signal. Decreasing voxel size and increasing the acquisition matrix can also reduce artifact.^{14,15}

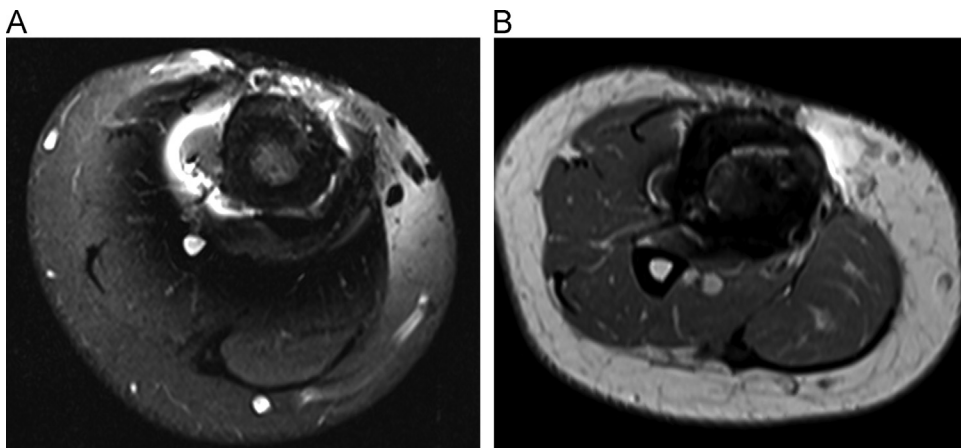


Fig. 5. (A) Metal artifact: axial T2-weighted image with fat saturation of the tibia and fibula demonstrating metal artifact caused by an intramedullary rod resulting in a large area of signal displacement with pile-up and signal void. (B) Metal artifact: axial T2-weighted image with metal reduction protocol consisting of the removal of fat saturation and broadening the imaging bandwidth.

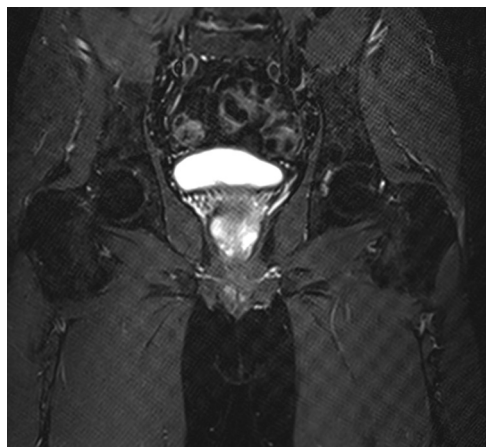


Fig. 6. Data corruption. Coronal STIR image of the pelvis with data corruption during image acquisition creating a cross-hatch pattern across the affected image.

Technologic Failures

Technology-related artifacts will be addressed in 2 settings as follows: artifacts resulting from the actual imaging formation process caused by suboptimal data acquisition or processing or artifacts resulting from intrinsic RF coil limitations or failures.

Data Corruption

When an erroneous calculation or data spike occurs during the processing of acquired data, this affects the entire acquisition.⁵ This data corruption or “data error” result in the creation of a visually repetitive pattern of lines or cross-hatching that covers the entire image, giving it a textured appearance as if printed on canvas (Fig 6). Occasionally, this erroneous data spike can result from an electromagnetic discharge (static electricity) occurring during data acquisition that is produced by the hospital sheets or the patient’s clothing.³ Unfortunately, the only solution is to re-acquire the corrupted data or slice.

Aliasing

Aliasing can be both frequency and phase related. Frequency aliasing occurs when the sampling frequency is below the Nyquist rate (the Nyquist rate being twice the highest acquired signal

frequency), but it is uncommon in modern equipment that use bandpass filters to suppress unwanted frequencies.^{3,5} Phase aliasing is more common, wherein a part of anatomy that is actually outside of the FOV is “wrapped” into view. The cause for this artifact is evident when one considers that a significant portion of the patient’s body is typically excluded from the imaging FOV, but it is nonetheless exposed to the magnetic field. This anatomy located outside of the FOV still experiences gradients; however, along the phase-encoding direction unique phase values are restricted to the FOV, thus, the regions beyond the FOV would be assigned redundant phase values, causing signal to be wrapped back into the FOV overlapping the anatomy within the FOV (Fig 7).^{2,3,16}

Although there are several ways to reduce this artifact, the simplest option is to avoid exciting anatomy outside the desired imaging FOV. For instance, this is achievable by using an appropriate transmit-receive surface or extremity coil to reduce the volume of the anatomy exposed to the RF excitation and signal reception.^{2,16} Alternatively, broadening the FOV reduces the percentage of anatomy excluded.² However, increasing the FOV requires a shallower frequency-encoding gradient to allow the same distribution of frequencies to be experienced across the anatomy as in the original FOV.² If neither of these options are desirable, a saturation band can be applied over the region of anatomy that is wrapping into the FOV to reduce the strength of the aberrant signal.²

3D imaging also suffers from wraparound along the slice dimension, where data from the first slice may wrap into the last (or vice versa). If these slices are beyond the region of interest, these peripheral slices can be ignored.² Aliasing can also be regarded as the result of under-sampling the volume. When this occurs, the obvious solution is to increase the sampling frequency, which increases scan time in the case of added phase sampling, unless the number of excitations is reduced.

Truncation

Truncation is an artifact, often referred to as “Gibbs artifact or ringing,” which results from an insufficient data sampling. The artifact occurs at boundaries between tissue types with dramatically different signal contrasts. Owing to a finite number of frequencies sampled, there is insufficient data to appropriately describe this sharp interface during image reconstruction. This phenomenon is seen between fibrous structures such as the

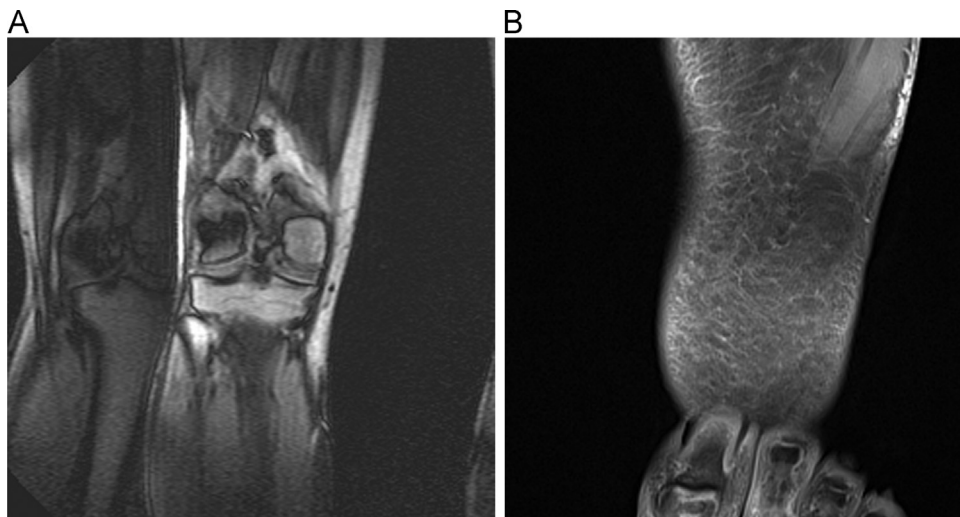


Fig. 7. (A) Phase-related aliasing artifact: coronal gradient echo image of the knee with the contralateral leg wrapped into the field of view. (B) Phase-related aliasing artifact: axial T2-weighted fat saturated image of the foot with the toes wrapping over the heel.

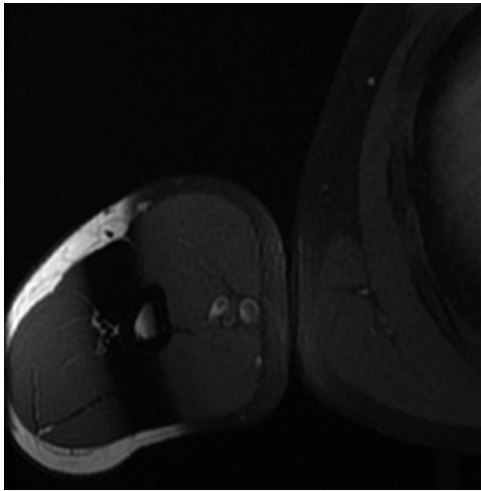


Fig. 8. Failed fat suppression. Axial T2-weighted image with fat saturation demonstrates failed fat suppression along the lateral arm in a larger patient.

menisci and joint fluid, or the spinal cord and cerebral spinal fluid; the alternating bright and dark bands can be mistaken for a meniscal tear or spinal cord syrinx, respectively.^{2,5,16} Solutions are to either decrease the pixel size or to increase the high-frequency sampling in an effort to account for and thus appropriately display more of the high frequencies needed to delineate strikingly different tissue types correctly.^{2,16}

RF Coil Limitations

RF coils are often selected with the intent of improving the signal to noise ratio, and thus image quality. However, artifacts occur when there is variability within the RF magnetic field produced by the coil. Most commonly, this occurs at the coil boundaries and near the peripheral regions of a coil's sensitive range, presenting as anatomic distortion and failed fat suppression.^{5,9} This latter complication is increasingly common with larger patients, when the anatomy surpasses the fixed coil size (Fig 8).⁹

Another consideration is actual coil failure, which may be seen as a dramatic loss in signal to noise, or in the case of a multi-channel coil, as areas of decreased signal with respect to areas with properly functioning coil elements.

External RF pulses extrinsic to the MR system, often resulting from inadequate shielding, an open door, or electronic devices such as cell phones or pagers within the MR suite, can cause a “zipper” artifact, dots, or lines.^{2,5,17} These RF interference artifacts often present as a line of alternating bright and dark dots or dashes measuring 1–2 pixels in width that are oriented perpendicular to the frequency-encoding gradient.⁵ This means that the artifact appears along the phase-encoding direction of the image at the one frequency-encoding value corresponding to the erroneous signal (Fig 9). The solution is to remove the offending device if possible and ensure that the scanner door is completely closed. If the artifact persists, then the integrity of the room shielding should be inspected.

Another common instance of image degradation by extraneous RF pulses is when the RF pulse used in the acquisition of one slice “bleeds” into and saturates the protons of the neighboring slice. This is referred to as “cross-talk.”⁹ When this next slice is acquired there is a dampening in the degree of possible proton excitation; essentially, those protons having been presaturated.¹⁶ This is caused by the fact that an RF pulse transmission is not pure. Each RF pulse consists of a range of frequencies on either side of the desired frequency, and these frequencies may result in excitation

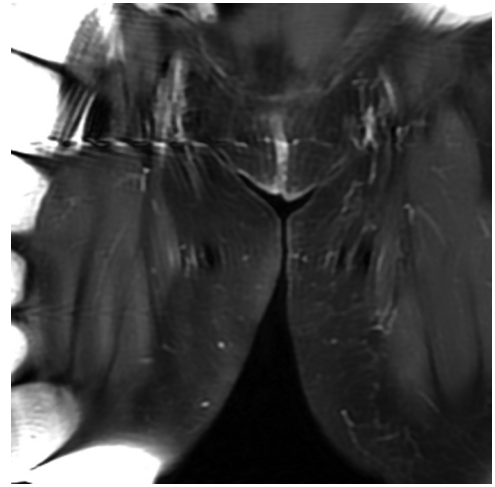


Fig. 9. RF pulse “zipper” artifact. Coronal T2-weighted image with fat saturation demonstrates a line of alternating bright and dark dots or dashes measuring 1–2 pixels in width along the phase-encoding direction of the image compatible with “zipper” artifact. The failed fat saturation along the periphery of the patient is a separate artifact.

of anatomy beyond the boundaries of the acquired slice. Thus, the artifact is minimized by including gaps of space between acquired slices that are at least 10%–20% of the acquired slice width, depending on the imaging technique used.^{2,5,16} Another option to reduce this cross-talk artifact is interleaving acquisitions by acquiring alternating slices during 2 acquisitions.⁹

Conclusion

The increasing use of MRI mandates a familiarity with the fundamental principles of image creation to both appropriately identify and fix artifacts when they occur. As imaging has become a mainstay of modern medicine, often utilized and interpreted by clinicians other than radiologists, it may be that understanding the fundamentals of imaging science would be what defines and separates the future radiologist from their peers.

References

- Schild Hans. MRI Made Easy. 1st ed. Berlin, Germany: H. Heenemann GmbH & Co; 1990, 1–45.
- Hashemi RH, Bradley WG Jr, Lisanti CJ. Artifacts in MRI. In: Mitchell CW, ed. MRI: The Basics. 3rd ed. Philadelphia, PA: Lippincott Williams & Wilkins; 2010. p. 185–213.
- Hoff MN, Andre JB, Stewart BK. Artifacts in MRI. In: Magnetic Resonance Imaging. Saba L ed. Oxford, UK: Taylor and Francis; currently accepted and in press for November 2015 publication.
- Morelli John JN, Runge VM, Ai F, et al. An image-based approach to understanding the physics of MR artifacts. RadioGraphics 2011;31:849–66.
- Bushburg JT, Seibert AJ, Leidholdt EM Jr, et al. The Essential Physics of Medical Imaging. 3rd ed. Lippincott Williams & Wilkins; 2012, 477–93.
- Singh DR, Chin MS, Peh WC. Artifacts in musculoskeletal MR imaging. Semin Musculoskelet Radiol 2014;18:12–22.
- Bydder M, Rahal A, Fullerton GD, et al. The magic angle effect: A source of artifact determinant of image contrast, and technique for imaging. J Magn Reson Imaging 2007;25:290–3000.
- Mengiardi B, Pfirrmann CW, Schöttle PB, et al. Magic angle effect in MR imaging of ankle tendons: Influence of foot positioning on prevalence and site in asymptomatic subjects and cadaveric tendons. Eur Radiol 2006;16(10): 2197–206.
- Morrison W, Sanders T. Problem Solving in Musculoskeletal Imaging. 1st ed. Philadelphia PA: Mosby; 2008, 24–34.
- Brateman L. Chemical shift imaging: A review. AJR Am J Roentgenol 1986;146: 971–80.
- Hargreaves BA, Worters PW, Pauly KB, et al. Metal-induced artifacts in MRI. AJR Am J Roentgenol 2011;197:547–55.

12. Hargreaves BA, Chen W, Lu W, et al. Accelerated slice encoding for metal artifact correction. *J Magn Reson Imaging* 2010;31(4):987–96.
13. Harris CA, White LM. Metal artifact reduction in musculoskeletal magnetic resonance imaging. *Orthop Clin N Am* 2006;37:349–59.
14. Suh JS, Jeong EK, Shin KH, et al. Minimizing artifacts caused by metallic implants at MR imaging: Experimental and clinical studies. *AJR Am J Roentgenol* 1998;171(5):1207–13.
15. Lee MJ, Kim S, Lee SA, et al. Overcoming artifacts from metallic orthopedic implants at high-field strength MR imaging and multi-detector CT. *Radiographics* 2007;27:791–803.
16. Stadler A, Schima W, Ba-Ssalamah A, et al. Artifacts in body MR imaging: Their appearance and how to eliminate them. *Eur Radiol* 2007;17:1242–55.
17. Zhuo J, Gullapalli RP. AAPM/RSNA physics tutorial for residents: MR artifacts, safety and quality control. *Radiographics* 2006;26:275–97.