Clinical Protocol Challenges in MSK High Field (3T and 7T)

Garry E. Gold, M.D.
Associate Professor of Radiology and (by courtesy)
Bioengineering and Orthopaedics
Stanford University

Introduction

The physical principles that underlie MRI are very applicable to everyday musculoskeletal imaging. The lack of motion and need for high resolution of most tissues in MSK MRI result in protocols being a trade-off between imaging time, resolution, and signal-to-noise ratio (SNR). Improvements in gradient systems and software are enabling a transition from multiple two-dimensional acquisitions to three-dimensional isotropic acquisitions. Fat suppression, or fat/water separation, is critical to providing good contrast in musculoskeletal imaging.

In general, the intrinsic signal to noise ratio (SNR) available in a MRI experiment is a function of the strength of the main magnetic field, the volume of tissue being imaged, and the radiofrequency coil being used. In theory, if the coil and the subject are equivalent, imaging at 3.0T should provide twice the intrinsic SNR of imaging at 1.5T (1). However, changes to tissue relaxation times, sensitivity to magnetic susceptibility, and the chemical shift difference between fat and water all influence image quality at 3.0T. Thus, careful adjustment of the imaging protocols is necessary to optimize imaging at 3.0T. New whole body systems at 7.0T are also available, and considerable changes to existing methods for those systems will be needed for routine imaging.

Tissue Contrast

Prior measurements of relaxation times at 4.0T showed increases of T1 of 70-90% and decreases of T2 of 10-20% compared with 1.5T (2). Recent measurements of these values in musculoskeletal tissues at 3.0T show a decrease in T2 of about 10% and an increase in T1 of about 15-20% (3). The changes in these parameters affect the choice of

TR and TE that are appropriate for 3.0T, and ultimately impact the contrast and SNR of the images produced.

In MRI, tissue contrast is determined by a number of variables, including the TR and TE chosen by the scan operator, the T1 and T2 relaxation times of the tissues being studied, and the use of fat saturation. At 3.0T, the chosen TR and TE should reflect the underlying tissues being imaged and the contrast desired. In most cases, since the T1 relaxation times have increased at 3.0T, the TR must be longer to achieve the same type of contrast seen at 1.5T. Similarly, the TE should be slightly shorter to account for decreases in T2 relaxation times. In gradient echo examinations, the flip angle should be lower to account for the increased T1 relaxation times. Since T2* effects are doubled at 3.0T versus 1.5T(4), TE needs to be shorter at 3.0T to produce similar contrast for those sequences. Relaxation times for MSK tissues at 7.0T are under investigation.

Chemical Shift Artifact

Since the resonant frequencies of fat and water are twice as far apart at 3.0T compared with 1.5T, chemical shift of fat pixels in the frequency-encoding direction is twice as great at a given imaging bandwidth (4). One area where chemical shift artifacts may affect diagnosis is in the spine, where intervertebral disks may appear larger or smaller depending on the bandwidth in the frequency direction (*Palmer, et al. ARRS 2003)*. Chemical shift is also an issue in diagnosis of cartilage thinning. Artifacts from motion or metal in the post-operative patient may present more problems at 3.0T than at 1.5T. Susceptibility from small pieces of metal left in and around the joint will be increased (4). Strategies for dealing with post-operative artifacts at 1.5T will also work at 3.0T, such as increasing the bandwidth and minimizing the use of gradient echo sequences (5).

RF Power Deposition

The resonant frequency at 3.0T (about 125 MHz) is twice that at 1.5T. This means that the radiofrequency (RF) power for excitation at 3.0T is four times higher than at 1.5T (6, 7). Use of shorter imaging sequences such as fast spin echo may reduce the RF

power deposition. Since the RF power deposited is a function of tissue volume excited, this is more of a problem with large body areas such as the hips than smaller areas such as the knee (7). Sequences that may suffer from high RF power deposition include fast or turbo spin-echo sequences with multiple 180-degree pulses. Recent advances in sequence design have led to using these sequences with lower amplitude refocusing pulses, at a cost of SNR. T1-rho imaging, which is used for detection of macromolecules in cartilage, uses high power RF pulses and may be limited at 3.0T and above.

Fat Saturation

At 3.0T, the chemical shift between fat and water resonance is twice that of 1.5T, or approximately 440 Hz(1). This means that fat saturation at 3.0T is easier than at 1.5T in the sense the peaks are farther apart. The length of the fat saturation pulses can be shortened from about 16 ms to 8 ms. The overhead time per slice spent in fat saturation at 3.0T during a multi-slice acquisition is less than at 1.5T. This means that if fat saturation is applied, more slices can be acquired at a given TR, slice thickness and bandwidth at 3.0T than at 1.5T.

Fat water separation methods are becoming popular in musculoskeletal MRI due to the ability to provide excellent separation in areas of poor field homogeneity. This includes the foot and the brachial plexus. These methods may also provide a means to do water only imaging with T1 contrast in the presence of metal or severe inhomogeneity. One example of such a technique is IDEAL (Iterative Decomposition of water and fat with Echo Asymmetry and Least-squares estimation) (8-10).

New Contrast Mechanisms

Several new contrast mechanisms have been proposed for use in musculoskeletal imaging. These include delayed gadolinium enhanced MRI of cartilage (dGEMRIC), T1rho imaging, and T2 mapping for looking at macromolecular status in articular cartilage (11-13). Imaging at sodium frequency has also been used to estimate proteoglycan content in articular cartilage (14, 15). Each of these methods has trade-offs in ease of use, RF power deposition, and overall signal and resolution.

Another area of recent research in musculoskeletal imaging is ultra-short echo time (uTE) imaging (16). Most tissues of interest such as ligaments, menisci, cortical bone, and tendons, have short T2 relaxation times (17). Several methods have been described to get signal from these tissues, and perhaps diagnose pathology at an earlier stage (18). Many methods are based upon projection-reconstruction that begins at the origin of *k*-space to minimize echo times.

Isotropic Imaging at 3.0T

Sequences such as 3D-FSE-CUBE (19) and SPACE have a fast spin-echo contrast and routinely use parallel imaging to reduce scan times to an acceptable range. These methods also use flip angle modulation to reduce blurring during the echo train (20). Other new methods for 3D MRI include vastly interpolated projection reconstruction (VIPR) and balanced steady-state free precession. Increased resolution a may be helpful in several problem areas of musculoskeletal imaging (21). Imaging of these areas at very high resolution may require multiple signal averages for either SNR, to avoid phase wrap, or both. If imaging is done with fat suppression, lowering the imaging bandwidth will improve the overall SNR. If T2-weighted imaging is used, increasing the echo train length for additional speed is acceptable. However, if T1-weighted or proton density (short TE) imaging is performed, as short echo train length may be preferable to avoid blurring (22).

Protocol Design at High Field

MSK protocols are designed to target an anatomic area of interest with sufficient resolution and contrast to make a diagnosis. This means that the best protocols are problem specific. For example, a “rule-out fracture” protocol may be done at lower resolution or more rapidly than a “assess cartilage damage” protocol. In general, most protocols are designed to be robust to a number of possible disorders such that a general protocol will cover most clinical situations.

At 3.0T, MSK protocols may be designed for high spatial resolution and image quality, or designed for speed and throughput. The specific parameters depend upon the

coil and imaging system, but a high quality knee MRI may be done in about 10 minutes at 3.0T at relatively lower resolution, but may take up to 40 minutes for a high-resolution examination. Patient motion may become an issue with longer exams.

At high field, the issues of SAR and scan efficiency may come into play with sequences such as fast spin-echo that use high RF power. Multi-coil transmit may help with problems of RF penetration and B1 inhomogeneity. Imaging at 3T and 7T may enable routine clinical use of novel biochemical methods such as sodium MRI, uTE MRI, or gagCEST MRI.

Conclusions

Magnetic Resonance Imaging provides a powerful tool for the imaging and understanding of the connective tissues of the musculoskeletal system. The fundamental trade-off between image resolution and SNR still limits our ability to image *in-vivo* with high resolution in an efficient manner. 3.0T systems may allow for fast routine imaging or higher resolution studies. 7.0 T systems, when optimized and more routinely available, will improve things further still. New contrast mechanisms such as uTE MRI and multinuclear MRI may result in diagnosis at an earlier, more treatable stage of disease.

References

1. Collins CM, Smith MB. Signal-to-noise ratio and absorbed power as functions of main magnetic field strength, and definition of "90 degrees " RF pulse for the head in the birdcage coil. Magn Reson Med 2001; 45:684-691.
2. Duewell SH, Ceckler TL, Ong K, et al. Musculoskeletal MR imaging at 4 T and at 1.5 T: comparison of relaxation times and image contrast. Radiology 1995; 196:551-555.
3. Gold GE, Han E, Stainsby JA, Wright GA, Brittain JH, Beaulieu CF. Musculoskeletal MRI at 3.0 Tesla: Relaxation Times and Image Contrast. AJR Am J Roentgenol 2004; 183:343-351.
4. Peh WC, Chan JH. Artifacts in musculoskeletal magnetic resonance imaging: identification and correction. Skeletal Radiol 2001; 30:179-191.
5. White LM, Buckwalter KA. Technical considerations: CT and MR imaging in the postoperative orthopedic patient. Semin Musculoskelet Radiol 2002; 6:5-17.
6. Shellock FG. Radiofrequency energy-induced heating during MR procedures: a review. J Magn Reson Imaging 2000; 12:30-36.
7. Brix G, Seebass M, Hellwig G, Griebel J. Estimation of heat transfer and temperature rise in partial-body regions during MR procedures: an analytical approach with respect to safety considerations. Magn Reson Imaging 2002; 20:65-76.
8. Reeder SB, Pelc NJ, Alley MT, Gold GE. Rapid MR imaging of articular cartilage with steady-state free precession and multipoint fat-water separation. AJR Am J Roentgenol 2003; 180:357-362.
9. Reeder SB, Pineda AR, Wen Z, et al. Iterative decomposition of water and fat with echo asymmetry and least-squares estimation (IDEAL): Application with fast spin-echo imaging. Magn Reson Med 2005; 54:636-644.
10. Reeder SB, Pineda AR, Yu H, McKenzie C, Brau A, Gold GE. Water-Fat Separation with IDEAL-SPGR. In:Thirteenth Annual ISMRM. Miami, 2005.
11. Burstein D, Gray M. New MRI techniques for imaging cartilage. J Bone Joint Surg Am 2003; 85-A Suppl 2:70-77.
12. Mosher TJ, Dardzinski BJ. Cartilage MRI T2 relaxation time mapping: overview and applications. Semin Musculoskelet Radiol 2004; 8:355-368.
13. Li X, Han ET, Ma CB, Link TM, Newitt DC, Majumdar S. In vivo 3T spiral imaging based multi-slice T(1rho) mapping of knee cartilage in osteoarthritis. Magn Reson Med 2005; 54:929-936.
14. Boada FE, Shen GX, Chang SY, Thulborn KR. Spectrally weighted twisted projection imaging: reducing T2 signal attenuation effects in fast three-dimensional sodium imaging. Magn Reson Med 1997; 38:1022-1028.
15. Borthakur A, Shapiro EM, Beers J, Kudchodkar S, Kneeland JB, Reddy R. Sensitivity of MRI to proteoglycan depletion in cartilage: comparison of sodium and proton MRI. Osteoarthritis Cartilage 2000; 8:288-293.
16. Robson MD, Gatehouse PD, Bydder M, Bydder GM. Magnetic resonance: an introduction to ultrashort TE (UTE) imaging. J Comput Assist Tomogr 2003; 27:825-846.
17. Gold GE, Pauly JM, Macovski A, Herfkens RJ. MR spectroscopic imaging of collagen: tendons and knee menisci. Magn Reson Med 1995; 34:647-654.

18. Gatehouse PD, Thomas RW, Robson MD, Hamilton G, Herlihy AH, Bydder GM. Magnetic resonance imaging of the knee with ultrashort TE pulse sequences. Magn Reson Imaging 2004; 22:1061-1067.
19. Gold GE, Busse RF, Beehler C, et al. Isotropic MRI of the knee with 3D fast spin-echo extended echo-train acquisition (XETA): initial experience. AJR Am J Roentgenol 2007; 188:1287-1293.
20. Mugler JP, 3rd, Bao S, Mulkern RV, et al. Optimized single-slab three-dimensional spin-echo MR imaging of the brain. Radiology 2000; 216:891-899.
21. Potter HG, Linklater JM, Allen AA, Hannafin JA, Haas SB. Magnetic resonance imaging of articular cartilage in the knee. An evaluation with use of fast-spin-echo imaging. J Bone Joint Surg Am 1998; 80:1276-1284.
22. Hargreaves BA, Gold GE, Beaulieu CF, Vasanawala SS, Nishimura DG, Pauly JM. Comparison of new sequences for high-resolution cartilage imaging. Magn Reson Med 2003; 49:700-709.

Multiple Choice Questions (correct answer in bold)

1. Radiofrequency power deposition
   a) Decreases with increased main field strength
   b) Is constant at any field strength
   c) Does not depend on coils or patient weight
   d) Increases with main field strength

2. uTE MRI is useful for:
   a) Seeing long T2 tissues such as synovial fluid
   b) Assessment of proteoglycan in cartilage
   c) Obtaining signal from short T2 tissues such as meniscus and tendon
   d) Rapid isotropic acquisitions