MRI of the Acute Injured Knee

Magnetic resonance imaging (MRI) has become a mainstay in the assessment of internal derangement of the knee (Carmichael et al., 1997). MR imaging prior to surgery increases diagnostic confidence (Maurer et al., 1997). It also influences clinical practice by identifying alternative diagnoses, e.g., for an osteochondral injury that clinically may mimic meniscal tears, different surgical approaches exist for many cases. MRI helps avoid unnecessary arthroscopy (Ruwe et al., 1992; Spiers et al., 1993; Mackenzie et al., 1996; Bui-Mansfield et al., 1997; Carmichael et al., 1997).

This unit presents the standard protocol for imaging injured knees in a clinical setting. The parameters given in this unit are derived from a 1.5 T machine and may need to be altered slightly depending on the main magnetic field strength and the equipment manufacturer.

BASIC PROTOCOL

IMAGING THE KNEE

Magnetic resonance imaging scans can be run at a range of different field strengths. The lower signal-to-noise ratio (SNR) inherent in low field systems means that trade-offs must be made in the field of view, number of excitations (or number of acquisitions), slice thickness, and acquisition matrix size to maintain adequate signal. Whenever the spatial resolution is kept constant, the lower SNR of a low field system generally results in the need to reduce the receiver bandwidth and to increase the number of excitations in order to increase the signal. These alterations in protocol result in a longer acquisition time. On high field systems, a general protocol of 4 to 5 sequences will result in a comprehensive evaluation of the injured knee generally in <25 min.

In general, protocols utilizing a short T_E sequence (T_1, proton density-weighted or gradient echo) and a long T_E sequence (T_2-weighted), especially with fat saturation, are useful in the musculoskeletal system.

Regardless of the primary disease process suspected clinically, the end result, anatomically and pathologically, of acute injuries is a T_2-weighted prolongation (edema and/or hemorrhage). Therefore, a sensitive T_2-weighted examination is needed and it is generally felt that a fast spin echo T_2-weighted sequence with fat saturation or short tau inversion recovery (STIR) sequence works best. In the authors' experience, the short T_E sequence of choice for the evaluation of meniscal disorders is a standard (conventional) spin echo or gradient echo sequence as fast spin echo (FSE) sequences tend to be blurry and are slightly less sensitive. Recently, improvements in gradients and coils have made the use of high resolution fast spin echo proton density sequences more practical.

The following five sequences (including one optional sequence) encompass the authors' preferred Basic Protocol.

Table A23.1.1 provides a list of the hardware necessary to perform the procedure, along with appropriate parameters. Intravenous or intra-articular contrast agent administration is neither necessary nor recommended in an acute trauma setting.

NOTE: Be sure that technicians and nurses have immediate access to any emergency equipment that may be relevant to a given study, or that may be needed for a particular patient, such as a crash cart or oxygen.

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Table A23.1.1 Equipment Parameters for Standard Knee Imaging

Coil type	Circumferential extremity coil with a transmit, receive, quadrature, or phase array design
Gradient coil strength	25 mT/m (or whatever the system permits)
Motion cushions	Helpful
Use of contrast agents	Not necessary

Set up patient and equipment

1. Interview the patient to ensure that there are no contraindications for the MRI exam such as cardiac pacemakers or other ferromagnetic materials. Find out if the patient has any health conditions that may require the presence of any special emergency equipment during the scanning procedure, or necessitate any other precautions.

   Standard screening forms (APPENDIX 1) are generally used for all patients scanned in MRI systems.

   Any ferromagnetic metals may be a health hazard to the patient inside the magnet, and may also affect the imaging quality. If in doubt as to the exact composition of the devices, it is best to exclude patients with any metal implants; see Shellock (1996) for a discussion of which implants may be safely scanned using magnetic resonance.

   The patient (or volunteer) may be accompanied into the magnet, by someone who can sit through the scan and comfort the patient as needed. This accompanying person must also be screened to ensure the absence of loose metal objects on the body or clothing.

2. If the scan is a research protocol, have the patient sign any necessary consent forms.

3. Ask the patient to remove all jewelry and change into a gown to eliminate any metal that might be found in clothing.

4. Have the patient wash off any mascara and other makeup in order to avoid local tissue heating and image artifacts.

5. Inform the patient of what will happen during the procedure, what he or she will experience while in the magnet, and how to behave including the following:

   a. If earphones or headphones are used to protect the ears from the loud sounds produced by the magnet, the patient will be asked to wear these, but will be able to communicate at any time during the examination.

   b. The patient will be given a safety bell or similar equipment to request assistance at any time (demonstrate how it works).

   c. In order to obtain good results, the patient should not move or talk during each scan—i.e., as long as the banging sound continues. Between the scans, talking is allowed in most cases, but should be avoided when comparative positional studies are being performed; the patient will be informed when this is the case.

   d. Nevertheless, the patient may call out at any time if he or she feels it is necessary.

6. Have the patient positioned on the table with feet toward the magnet. Either before or right after the patient lies down, set up any monitoring equipment that is to be used.

7. Center the patient in a knee coil at the region where the key information is needed. Make sure that the knee is constrained to prevent motion, especially if high resolution scans are to be run.

   Generally, the patient's knee is fixed in a straight horizontal neutral position. The comfortable installation of the patient at the beginning of the study is important to limit motion

Figure A23.1.1 Fast spin echo proton density image with fat saturation. Note the bone trabecular injury posterolaterally (straight arrow), the torn ACL in the notch of the knee (curved arrow), and the extensive soft tissue damage (arrowheads).

artifacts. Care should be exercised in positioning the cushions and pads around the knee in the extremity coil to make the examination as comfortable as possible.

8. If needed, place a pillow under the patient's head to make him or her more comfortable.

9. Use the centering (laser) light to position the injured knee to the lower third of the patella and put the patient into the center of the bore.

10. If the patient is not able to hold still, provide an appropriate sedative.

Sequence 1: Transverse fast spin echo proton density to T_2-weighted image with fat saturation (localizer; Fig. A23.1.1)

11. To validate the patient's position, run the localizer (scout scan) to ensure the correct location of the knee according to Table A23.1.2.

    In the following sequences, when necessary, choose the perpendicular (sagittal and coronal) planes using these transverse images.

Sequence 2: Sagittal dual spin echo proton density weighted/T_2-weighted sequence (Figs. A23.1.2 and A23.1.3)

12. Load the sequence for a sagittal dual spin echo proton density weighted/T_2-weighted sequence. Set the imaging parameters according to Table A23.1.3.

    Sagittal and coronal images can be obliqued to become orthogonal to the knee joint by using the femoral condylar surface as an orienting internal landmark to compensate for variability in patient positioning.

13. Alert the patient, and begin the scan.

Table A23.1.2 Primary Clinical Imaging Parameters for Sequence 1 (Scout Scan)

Patient position	Supine
Scan type	Fast spin echo
Imaging plane (orientation)	Transverse
Central slice or volume center	Laser light centered on the lower third of the patella
Echo time (T_E)	42 msec
Receiver bandwidth (RBW)	±11.36 kHz
Echo train length (ETL)	8
Repeat time (T_R)	3075 msec
Flip angle (FA)	90°
Fields of view (FOV_x, FOV_y)	120–140 mm, 120–140 mm
Resolution (Δx, Δy)	0.47–0.55 mm, 0.47–0.55 mm
Number of data points collected (N_x, N_y)	256, 256
Slice thickness (Δz)	5 mm
Number of slices	17
Slice gap	2 mm
Number of acquisitions (N_{acq})	2
No phase wrap (NPW)[a]	Yes
Saturation pulses	Frequency selective fat saturation
Scan time	3 min, 23 sec

[a]See Index of Terms in *UNIT A7.1*.

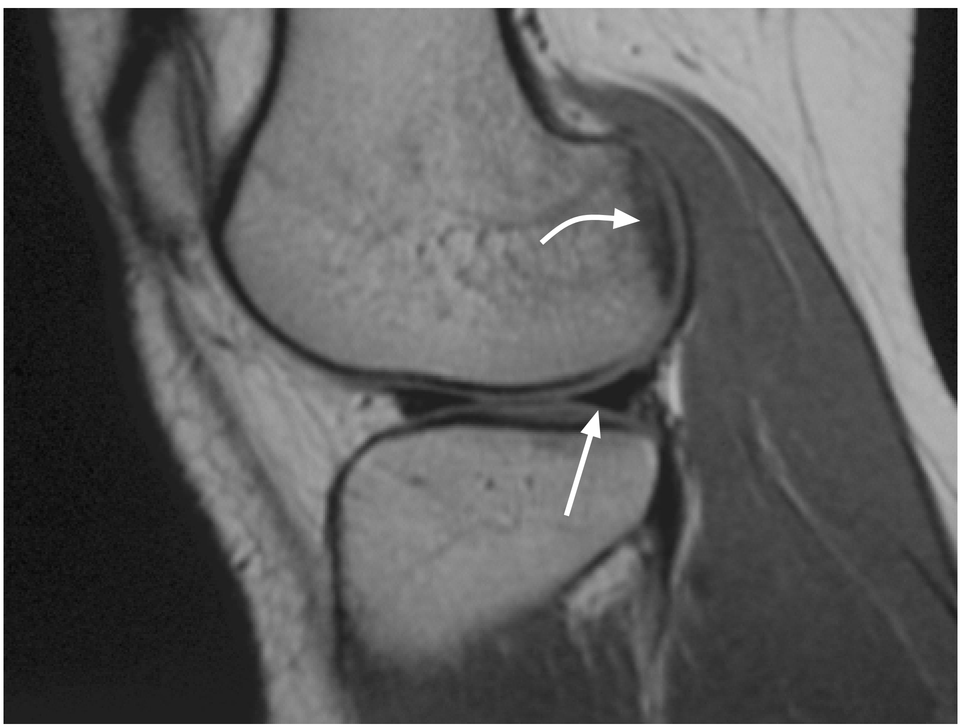

Figure A23.1.2 Proton density weighted sagittal image. Note the normal lateral meniscus (straight arrow) and the osteochondral injury of the posterior-most aspect of the lateral femoral condyle (curved arrow).

Figure A23.1.3 Standard spin echo T_2-weighted sagittal image. Note the torn ACL (straight arrow) and the relatively poor signal-to-noise ratio compared to fast spin echo images. The standard T_2-weighted image is chosen because the sequence is a double echo sequence including a standard spin echo proton density weighted echo, which is more sensitive for meniscal tears.

Table A23.1.3 Primary Clinical Imaging Parameters for Sequence 2

Patient position	Supine
Scan type	Dual spin echo proton density weighted/T_2-weighted
Imaging plane (orientation)	Sagittal
Central slice of volume center	Laser light centered on the lower third of the patella
Echo time (T_E)	20 msec and 80 msec
Repeat time (T_R)	2000 msec
Flip angle (FA)	90°
Fields of view (FOV_x, FOV_y)	120–140 mm, 120–140 mm
Resolution (Δx, Δy)	0.47–0.55 mm, 0.63–0.73 mm
Number of data points collected (N_x, N_y)	256, 192
Slice thickness (Δz)	4 mm
Number of slices	16
Slice gap	1 mm
Number of acquisitions (N_{acq})	1
No phase wrap (NPW)	Yes
Saturation pulses	No
Scan time	6 min, 39 sec

Figure A23.1.4 Fast spin echo proton density weighted sagittal image. This is a high resolution image utilizing the ZIP 512 feature.

Table A23.1.4 Primary Clinical Imaging Parameters for Sequence 3 (Optional)[a]

Patient position	Supine
Scan type	Fast spin echo proton density weighted
Imaging plane (orientation)	Sagittal
Central slice or volume center	Laser light centered on the lower third of the patella
Echo time (T_E)	27 msec
Echo train length (ETL)	6
Repeat time (T_R)	2200 msec
Flip angle (FA)	90°
Fields of view (FOV_x, FOV_y)	120 mm, 120 mm
Resolution (Δx, Δy)	0.38 mm, 0.47 mm
Number of data points collected (N_x, N_y)	320, 256
Slice thickness (Δz)	4 mm
Number of slices	17
Slice gap	0.5 mm
Number of acquisitions (N_{acq})	2
No phase wrap (NPW)	Yes
ZIP 512	Yes
Saturation pulses	No
Scan time	3 min, 11 sec

[a]Use autoshimming to shim the field and choose "phase correct" to remove the field inhomogeneity-caused artifact automatically.

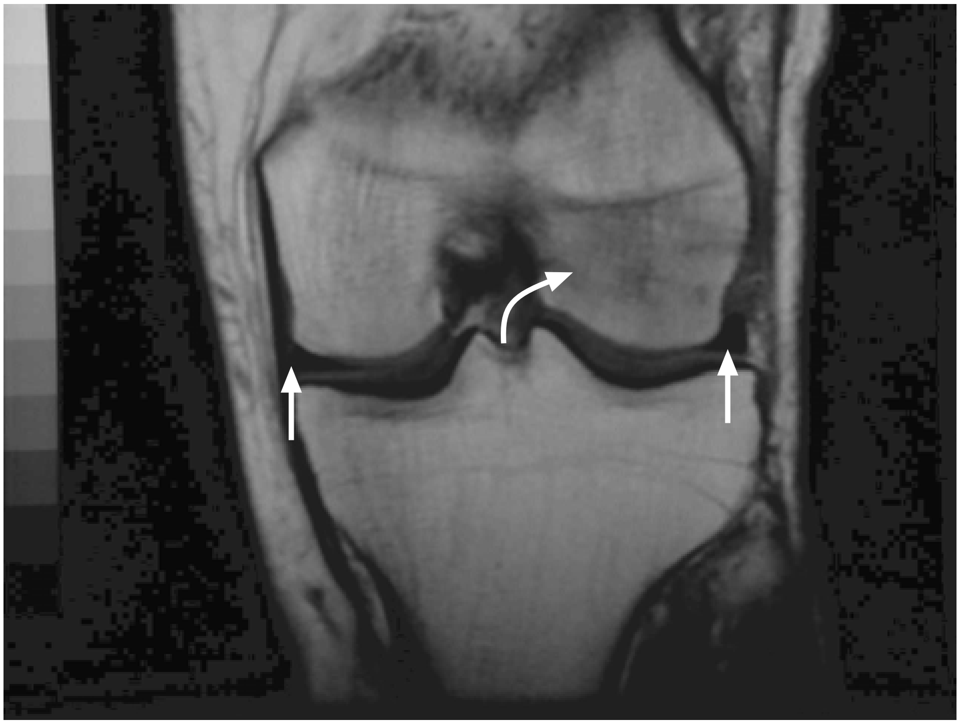

Figure A23.1.5 T_1-weighted coronal image. Note intact menisci (straight arrows) and subtle edematous changes in the lateral femoral condyle (curved arrow). The edema within the bone is shown to a much greater degree on the coronal proton density weighted fat saturated images.

Table A23.1.5 Primary Clinical Imaging Parameters for Sequence 4

Patient position	Supine
Scan type	T_1-weighted conventional spin echo
Imaging plane (orientation)	Coronal
Central slice or volume center	Laser light centered on the lower third of the patella
Echo time (T_E)	20 msec
Receiver bandwidth (RBW)	±15.63 kHz
Repeat time (T_R)	600 msec
Flip angle (FA)	90°
Fields of view (FOV_x, FOV_y)	120–140 mm, 120–140 mm
Resolution (Δx, Δy)	0.47–0.55 mm, 0.47–0.55 mm
Number of data points collected (N_x, N_y)	256, 256
Slice thickness (Δz)	5 mm
Number of slices	19
Slice gap	1 mm
Number of acquisitions (N_{acq})	2
No phase wrap (NPW)	Yes
Saturation pulses	No
Scan time	5 min, 15 sec

Figure A23.1.6 Fast spin echo proton density weighted coronal image with fat saturation. Note the extensive bone trabecular injury of the lateral femoral condyle (straight arrow). Note the normal hyaline articular cartilage of the edial femoral condyle (arrowheads).

Table A23.1.6 Primary Clinical Imaging Parameters for Sequence 5

Patient position	Supine
Scan type	T_2-weighted fast spin echo
Imaging plane (orientation)	Coronal
Central slice or volume center	Laser light centered on the lower third of the patella
Echo time (T_E)	54 msec
Echo train length (ETL)	10
Repeat time (T_R)	4200 msec
Flip angle (FA)	90°
Fields of view (FOV_x, FOV_y)	120–140 mm, 120–140 mm
Resolution (Δx, Δy)	0.47–0.55 mm, 0.47–0.55 mm
Number of data points collected (N_x, N_y)	256, 256
Slice thickness (Δz)	5 mm
Number of slices	18
Slice gap	1 mm
Number of acquisitions (N_{acq})	2
No phase wrap (NPW)	Yes
Saturation pulses	Frequency selective fat saturation
Scan time	3 min, 42 sec

Sequence 3: Sagittal fast spin echo proton density weighted sequence (optional; Fig. A23.1.4)

An alternative pulse sequence is the fast spin echo proton density weighted sequence utilizing a ZIP 512 feature that acquires the data at a 320 by 256 acquisition matrix and then manipulates the information to obtain a high resolution 512 by 512 display matrix image.

14. Run sequence 3 according to Table A23.1.4.

Sequence 4: Coronal spin echo T_1-weighted sequence (Fig. A23.1.5)

15. Load the sequence for a coronal spin echo T_1-weighted sequence. Set the imaging parameters according to Table A23.1.5.
16. Alert the patient, and begin the scan.

Sequence 5: Coronal fast spin echo intermediate to T_2-weighted sequence with fat saturation (Fig. A23.1.6)

17. Load the sequence for a coronal spin echo T_2-weighted sequence with fat saturation. Set the imaging parameters according to Table A23.1.6.
18. Alert the patient, and begin the scan.

COMMENTARY

Background Information

The knee is one of the most frequently injured regions of the body. Substantial progress has been made in magnetic resonance imaging since its initial application in 1984 for evaluating the meniscus. MRI is established as the diagnostic procedure of choice, supporting the physical examination and plain X-ray studies for virtually all suspected disorders of the knee. Moreover, MRI may serve as the "second" opinion before any surgical intervention.

The technique chosen in the Basic Protocol allows a reliable detection of common soft tissue and bony knee injuries.

Gradient echo imaging is an alternative to spin echo imaging for the meniscus. However, some studies have shown that the images are more limited than spin echo imaging in their ability to show ligament, muscle, tendon, and bone marrow abnormalities (Reeder et al., 1989; Solomon et al., 1989; Heron and Calvert, 1992). In addition, higher signal appears within a normal meniscus on gradient echo sequences, which can lead to an overestimation of meniscal tears and decrease the specificity and negative predictive value (Guckel et al., 1995). Gradient echo sequences are also vulnerable to susceptibility artifacts that occur in the vicinity of ferromagnetic substances (e.g., microscopic metallic particles after shavings from prior surgery) or gas (e.g., vacuum phenomenon in the knee joint).

FSE techniques have been recommended as some studies have shown no significant decrease in sensitivity for meniscal tears (Anderson et al., 1995; Escobedo et al., 1996). To prevent blurring with FSE and to allow an accurate diagnosis, the echo train length (ETL) must be relatively short (e.g., <4; Anderson et al., 1995; Escobedo et al., 1996). The imaging time needed for a fast spin echo sequence, compared to a conventional spin echo sequence, is reduced by, approximately, the echo train length. In the authors' experience, fast spin echo techniques are slightly less sensitive for the detection of meniscal tears, which is why standard spin echo is chosen, although, at some centers where the primary interpretations are supplied by the authors, fast spin echo techniques are employed.

In order to diagnose abnormalities of menisci accurately, short T_E sequences should be applied. Long T_E and T_R sequences (T_2-weighted images) are specific but not sensitive. In other words, visualization of fluid within the meniscal substance is highly specific for a meniscal tear on a T_2-weighted image. However, if one does not observe fluid in the meniscus on a T_2-weighted image, a tear is not ruled out. The authors' imaging routine protocols for the knee include T_2-weighting in three imaging planes to maximize the sensitivity and specificity for detecting ligamentous and tendinous pathology. Fat saturation further increases the sensitivity for detecting edema. T_1-weighted images alone are not adequate to appreciate areas of edema and hemorrhage in a disrupted ligament or tendon.

Critical Parameters and Troubleshooting

Magnetic resonance imaging of the injured knee is a potent, noninvasive tool. The suggested imaging method provides an approach to acquire a standard set of images that allows a thorough analysis. Even choosing a reliable protocol allows some potential artifacts to occur during the acquisition. The most common and important artifacts that may pose diagnostic difficulties are outlined in the following paragraphs together with solutions for remedies.

Magic angle artifact

Near the notch of the knee, the posterior horn of the lateral meniscus slopes upward. This approximates 55° of the external magnetic field and can lead to the magic angle artifact or diffuse increased signal intensity (Peterfy et al., 1994). To overcome the problem, the knee can be imaged in a slightly different position (the authors choose abduction) in order to exclude meniscal tears confidently.

Truncation artifact

The artifact results from under-sampling of data so that interfaces of high and low signal are represented incorrectly on the image. If utilizing a small acquisition matrix, the truncation artifact can result in an increased signal intensity through the meniscus that may appear as a tear. Using a higher acquisition matrix can minimize the artifact.

Motion artifact

Alternating increased and decreased signal lines occur with motion and can mimic meniscal tears (Mirowitz, 1994). It is highly recommended that this portion of the examination be repeated.

Vacuum phenomenon and ferromagnetic substances

Magnetic susceptibility of intra-articular gas and ferromagnetic substances may produce a low signal intensity void or blooming, especially on gradient echo images. This artifact may be mistaken for a meniscal tear or articular injury. Normal spin echo or fast spin echo sequences are much less vulnerable for these artifacts because of the 180° refocusing pulse.

Pulsation artifact

Popliteal artery pulsation artifacts lead to streaks in the MR image. They can be minimized by swapping the phase encoding and read directions.

Anticipated Results

The goal in studying the acute injured knee is the detection of soft tissue and bone abnormalities that could lead to worsening by repeat trauma or chronic instability and joint degeneration if not treated.

Magnetic resonance imaging offers a highly sensitive, specific, and accurate diagnosis of meniscal tears. In a comparison of 12 studies with a study volume of ≥200 subjects done by Rubin and Paletta (2000), the sensitivity for diagnosing a medial meniscal tear was 86% to 96% with a specificity of 84% to 94%. For lateral meniscal tears, the sensitivity was 68% to 86% and the specificity was 92% to 98%. The negative predictive value of these studies was 91%. This means that, in an arthroscopy in >9 of 10 cases, a meniscal tear will be confirmed. The protocol described in this unit supports these results.

Anterior cruciate ligament (ACL) ruptures are accompanied by medial meniscal tears in 43% and lateral meniscal tears in 66% with an overall incidence of meniscal tears of 65% to 80% (Stoller and Anderson, 1997).

Isolated ligamentous lesions can be detected reliably in clinical evaluation and MR imaging, but physical examinations becomes less reliable when multiple lesions exist (Rubin et al., 1998). Rubin et al. (1998) found an overall sensitivity and specificity for diagnosing ligament tears to be 94% and 99%, respectively, when one or more ligament was torn and 88% and 84%, respectively, when two or more supporting structures were torn. Clinical examination alone gave significantly less accurate results compared to the MR imaging. Hodler et al. (1993) showed a sensitivity, specificity, and accuracy for anterior cruciate ligament tears of 89%, 97%, and 95%, respectively. The imaging protocol provided in this unit offers comparable results to the cited studies and presents a noninvasive and accurate method for detecting ligamentous lesions of the knee.

Osteochondral defects in the knee can be detected very reliably and graded with fast spin echo T_2-weighted sequences with frequency selective fat saturation as described in sequences 1 and 5. Applying these sequences, Bredella et al. (1999) demonstrated that in combination of the axial and coronal fast spin echo

T_2-weighted sequences with fat saturation the sensitivity for the diagnosis of cartilage defects was 94%, specificity was 99%, and accuracy was 98%. Of these lesions, 90% were within one grade using MR imaging and arthroscopy applying a standard arthroscopic grading scheme adapted to MR imaging.

MR imaging affects the management and diagnosis of acute knee injuries by decreasing the numbers of arthroscopic procedures, improving diagnostic confidence, and supporting in management decisions (Maurer et al., 1997).

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