2 MRI Technical Considerations

2.1 Positioning and Fixation of the Knee

- It is not possible to diagnose ACL pathology using sagittal MR images acquired with fully or overextended knees.
- It is therefore important that the knee is slightly flexed within the coil (see Chap. 3 for more details).

2.2 Acquisition of Images in the Sagittal Plane

- It is essential that the range of image acquisition covers the entire femoral condyles and the tibial plateau from the medial to the lateral edge in the axial image (Fig. 2.1).
- In a typical adult male patient, more than 25 slices will be required at the slice thickness of 3 mm.
- In old days, acquisition of MR images in diagonal slices was severely limited by foldover artifacts. In those circumstances, it was necessary to externally rotate the distal lower limb by 15–20° to visualize ACL, which runs diagonally across the intercondyloid fossa, in sagittal images.
- Thanks to improvement in both hardware and software in MR imaging, this limitation has become less significant. However, one should be careful not to unnecessarily internally or externally rotate the knee to prevent distortion of ligamentous structures including cruciate and collateral ligaments (Fig. 2.2).

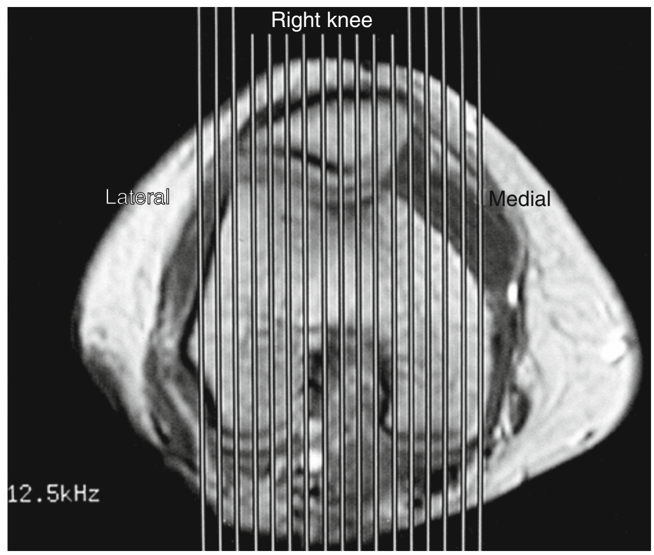

Fig. 2.1 **Setup of sagittal slices (right knee)**. In this example, there are only 17 slices, but ideally, there should be more than 25 slices at slice thickness of 3 mm to visualize fine changes in cartilage and menisci

- In sagittal acquisition, direction of phase encoding is usually anterior to posterior. In this case, however, images will be hindered by artifacts arising from blood flow in the popliteal artery and vein (Fig. 2.3). This can be prevented by setting the phase encoding direction to superior to inferior, but one should attempt to minimize foldover artifacts.

M. Niitsu et al., *Magnetic Resonance Imaging of the Knee*,
DOI 10.1007/978-3-642-17893-1_2,

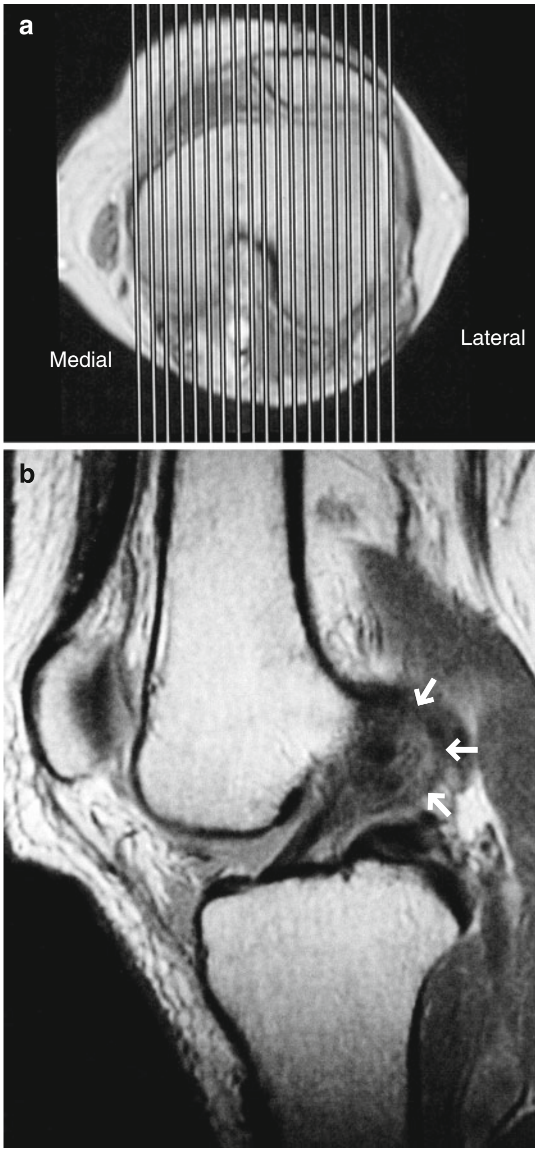

Fig. 2.2 Example of unsuccessful image acquisition due to excessive external rotation of the distal lower limb (right knee). Excessive external rotation of the distal lower limb leads to the direction of sagittal slice paralleling the lateral wall of intercondyloid fossa (**a**). In sagittal images, there will be partial volume effect from the bone cortex, which also hinders the delineation of ACL (**b**, *arrows*)

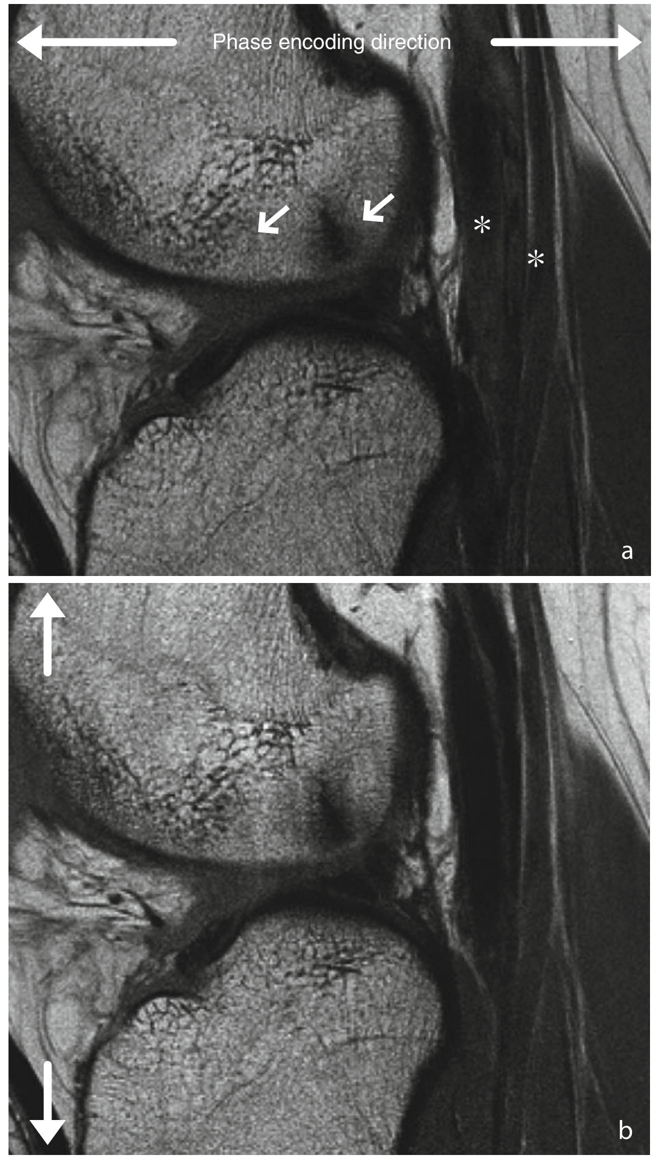

Fig. 2.3 Blood flow artifacts arising from inappropriate phase encoding direction. In sagittal acquisition, direction of phase encoding is usually anterior to posterior. In this case, however, images will be hindered by artifacts (**a**, *arrows*) arising from blood flow in the popliteal artery and vein (*). This can be prevented by setting the phase encoding direction to superior-to-inferior (**b**)

2.3 T1-Weighted and Proton Density-Weighted Fast Spin-Echo Sequences

- Although both T1- and T2-weighted images are automatically acquired at many institutions without much consideration, T1-weighted images do not have much value in delineating ligamentous and meniscal lesions.
- Normal ligaments and menisci show low intensity signals, and thus proton density- or intermediate-weighted images will allow better contrast with the surrounding cartilage and joint fluid (Fig. 2.4).
- Fast spin-echo (FSE) sequence requires much shorter acquisition time compare to conventional spin-echo (SE) sequence and enables acquisition of images with higher anatomical resolution. Thus, FSE is often utilized in knee MRI.
  – However, one needs to be cautious regarding the following issues:
    1. Echo train length (ETL) should be kept to the minimum to prevent occurrence of blurring of image.

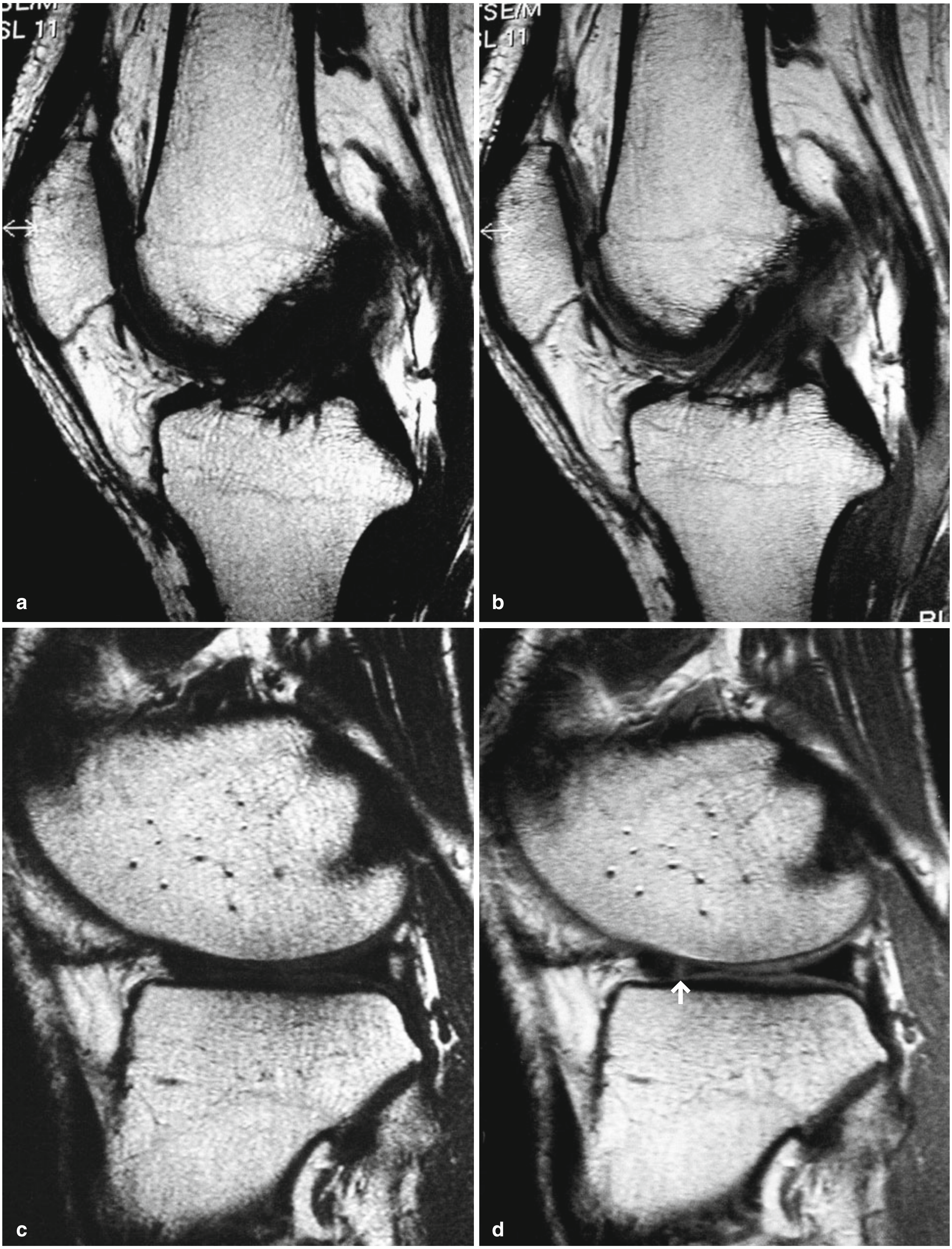

Fig. 2.4 Comparison of T1WI and intermediate-weighted (close to PDW) images. (**a**) and (**c**) T1WI (SE 350/14). (**b**) and (**d**) intermediate-weighted (close to PDW) images (FSE 1.324/17, ET 5). The latter demonstrates the margins of ACL and cartilage better than the T1WI, also with a better contrast of meniscal tear (**d**, *arrow*)

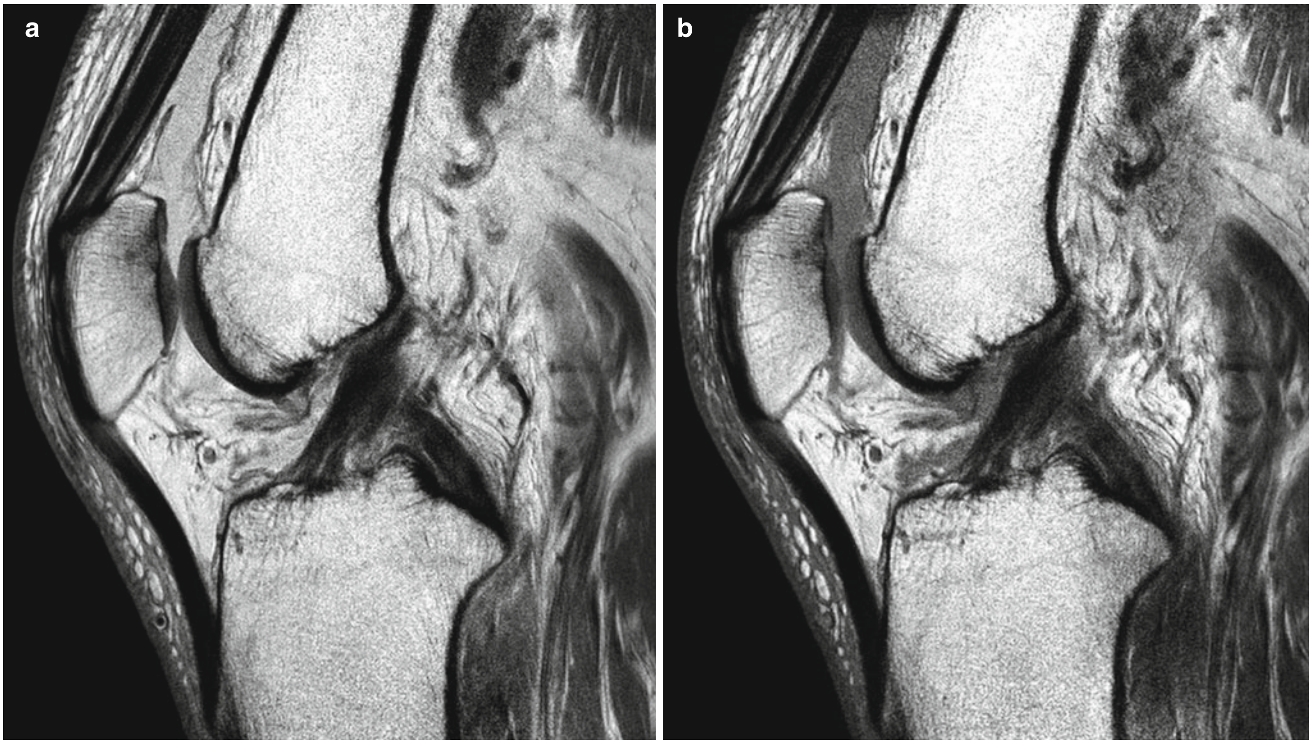

Fig. 2.5 PDWI with DRIVE (a), in which joint fluid is depicted as hyperintensity, and conventional PDWI (b). In (**a**), joint fluid is depicted as hyperintensity which creates better contrast with cartilage and ACL, allowing these structures to be more clearly delineated (FOV 150 mm, slice thickness 3 mm, slice gap 0.3 mm, 23 slices, 512 scan matrix, 864 ZIP, scan time 6 m)

2. Fat may be depicted as hyperintensity and may lower the contrast against meniscal lesions. This can be prevented by application of fat suppression.

- To acquire proton density-weighted FSE images, ETL should be kept to the minimum (max 5 or 6).
- Using proton density-weighted FSE sequences with water-highlighted technique (adding –90° pulse at the end of the echo train to forcefully recover vertical magnetization, such as DRIVE (Philips), FRFSE (GE), RESTORE (Siemens) and T2 Plus (Toshiba)), one can emphasize the T2-weighted contrast even with a relative short TR. Joint fluid will be depicted as hyperintensity and with better delineation of cartilage, ligaments, and menisci (Fig. 2.5).

2.4 Magic Angle Effect

- The magic angle effect is a phenomenon that results in artifactual hyperintensity in structures with ordered collagen, such as tendons and ligaments. This is because when collagen is oriented at 55° to the main magnetic field, dipole-dipole interactions becomes zero, resulting in a prolongation of T2 relaxation time.
- Care must be taken not to mistake this as a pathological finding such as a ligamentous tear.
- Magic angle effect is particularly notable with short TE sequences such as T1-weighted, proton density-weighted, or T2*-weighted (which is based on a gradient-recalled echo sequence using a low flip angle) sequences (Fig. 2.6).
- Magic angle effect can also affect the posterior horn of the lateral meniscus (Fig. 2.7).
- Magic angle effect can be avoided by using a long TE. Therefore, if magic angle effect is seen in T2*-weighted images, it can be eliminated by using SE sequences with a long TE or T2-weighted FSE sequences (Fig. 2.8).

References

Erickson SJ, et al. The “magic angle effect”: background and clinical relevance. Radiology. 1993;188:23–5.

Peterfy CT, et al. Magic-angle phenomenon: a case of increased signal in the normal lateral meniscus on short-TE MR images of the knee. AJR. 1994;163:149–54.

Fig. 2.6 Magic angle effect affecting the patellar tendon. T2*WI (GRE 560/14, flip angle 30°). Superior aspect of the patellar tendon exhibits localized hyperintensity (*arrows*). This phenomenon can be seen when the tendon is oriented at 55° to the main magnetic field (Bo, superior-inferior direction)

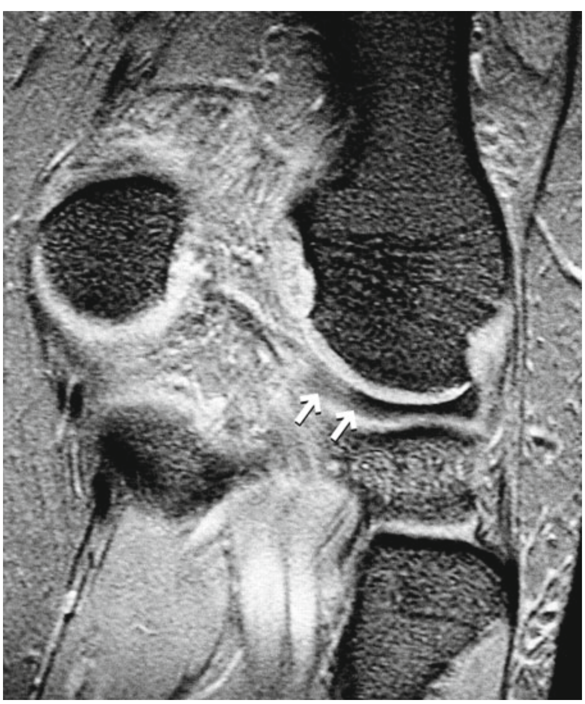

Fig. 2.7 Magic angle effect affecting the posterior horn of the lateral meniscus. Coronal T2*WI. Normal posterior horn of the lateral meniscus exhibits localized hyperintensity (*arrows*)

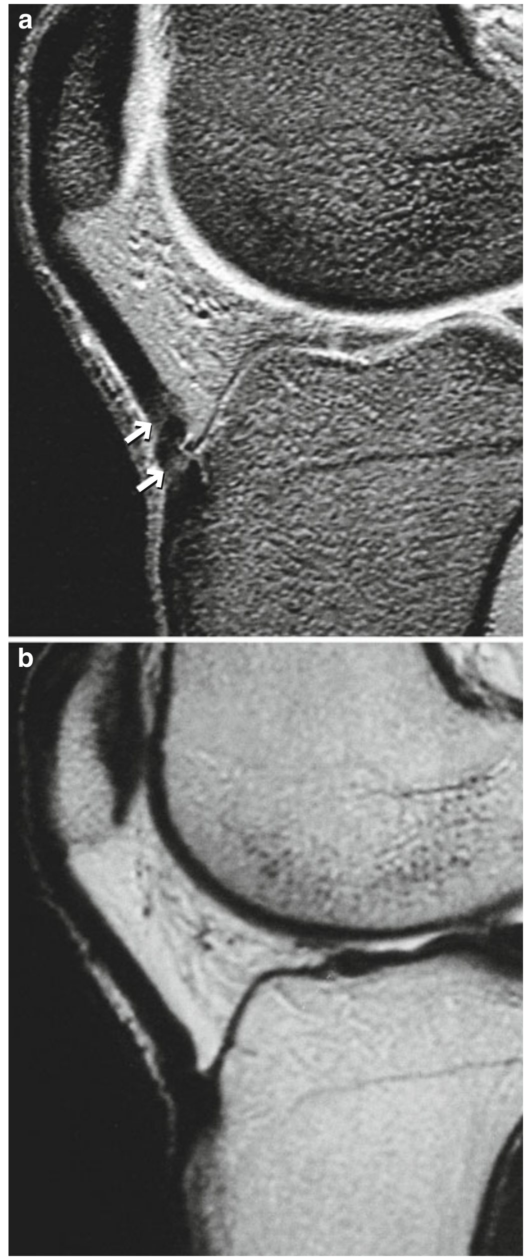

Fig. 2.8 TE-dependent nature of the magic angle effect. T2*WI (GRE 560/14, flip angle 30°) (**a**) and T2WI (FSE 3,000/90) (**b**). Localized hyperintensity at the inferior aspect of the patellar tendon seen in (**a**, *arrows*) disappears if TE is made longer (**b**)

T2-Weighted and T2*-Weighted Images

T2- and T2*-weighted images are useful sequences for knee imaging because it creates a good contrast between joint fluid (hyperintensity) and the lesions of ligaments and menisci. A gradient-recalled echo (T2*-weighted) sequence is particularly useful for delineating fine lesions. However, bearing in mind that the magic angle effect can cause an unwanted artifact, a long TE, SE, or FSE sequence should be added (either sagittal or coronal).

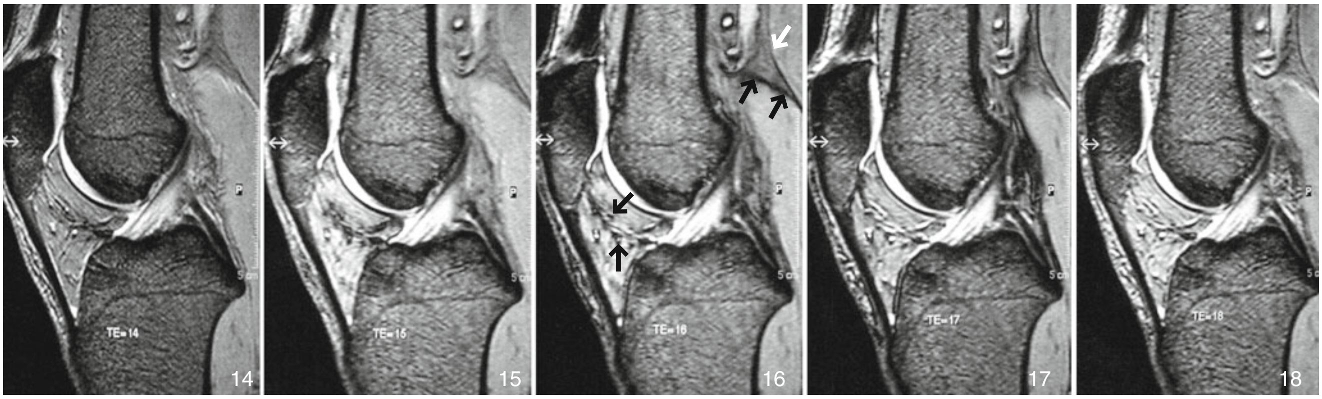

Fig. 2.9 **TE-dependent variability of signal strengths in gradient-recalled echo sequence** (From left, TE = 14, 15, 16, 17, and 18 ms). TE = 14 and 18 ms results in in-phase, while out-of-phase images will be created at TE = approx. 16 ms. When out-of-phase, signals from water and fat within the same pixel cancel out and the signals are lost. For example, the boundaries between subcutaneous fat and muscle or blood vessels will appear *black* ("boundary effect" (*black* and *white arrows*))

Table 2.1 TE (ms) representing in-phase and out-of-phase at 1.5 T

In-phase		4.5		9.0		13.5		18.0		22.5		27.0
Out-of-phase	2.3		6.8		11.3		15.8		20.3		24.8	

Table 2.2 TE (ms) representing in-phase at 1.0 and 1.5 T

In-phase at 1.0 T	6.8	13.5	20.3	27.0
In-phase at 0.5 T		13.5		27.0

2.5 In-Phase and Out-of-Phase Imaging

- In gradient-recalled echo sequences, signals from fat and water vary depending on TE.
- Resonance frequency of water is higher than that of fat by 3.5 ppm. This equates to about 220 Hz (63.9 MHz × 3.5 ppm) in a 1.5-T system.
- Thus, resonance frequencies of water and fat synchronize every 4.5 ms of TE (in-phase 220 Hz = 4.5 ms).
- When out-of-phase, signals from water and fat within the same pixel cancel out and the signals are lost. For example, the boundaries between subcutaneous fat and muscle or blood vessels will appear black ("boundary effect") (Fig. 2.9, Table 2.1).
- Multiply these values by 0.5 at 3.0 T, by 1.5 at 1.0 T, and by 3 at 0.5 T (Table 2.2)
- Note: TE = approx. 14 ms results in in-phase in any case

2.6 Usefulness of Axial Images

- Axial images add useful information to sagittal and coronal images, which are mainly used for assessment of ligaments running in the superior-inferior direction and menisci.
- Axial images are particularly suitable for delineation of the femoral attachment site of the cruciate ligaments, for example, partial tear of ACL which can be difficult to detect in sagittal images
- Cross-sectional areas of the hamstrings and patellar tendon, which is used for ACL reconstruction, can be measured
- Medial synovial plica and patellofemoral cartilage (the thickest cartilage of the knee joint) are clearly visualized in axial images and evaluation of patellar subluxation
- Fluid collection around menisci, including meniscal cysts, can also be clearly visualized

Reference

Roychowdhury S, et al. Using MR imaging to diagnose partial tears of the anterior cruciate ligament: value of axial images. AJR. 1997;168:1487–91.

2.7 Techniques for Fat Suppression

- Lesions that are present within the bone marrow, which comprises mostly fatty marrow, and subcutaneous fat should be assessed using fat suppression techniques.
- Chemical shift selective (CHESS) method, Chem Sat method = a method which utilizes the difference in resonance frequency between fat and water (224 Hz at 1.5 T) to add a suppress pulse only to fat signals.

Table 2.3 Comparison of fat suppression techniques

Technique	Pros	Cons
CHESS	Prolongation of scan time is little, and there is little limitation in the image acquisition techniques	Magnetic field inhomogeneity may lead to failure of fat suppression in an uneven fashion, particularly at the periphery of a large FOV
STIR	Homogeneous and almost perfect fat suppression can be expected	Need for addition of an IR pulse cause a number of restrictions in the image acquisition technique (especially the need for increased interslice gap and prolonged scan time)
Selective water excitation	Prolongation of scan time is minimal	Very sensitive to magnetic field inhomogeneity

- Short TI (tau) inversion recovery (STIR) = a method based on IR technique which sets the TI (tau) to be the null point for the fat signal.
- There is a new method called water selective excitation. This is an addition of an excitation pulse to the water, rather than adding a suppression pulse to the fat. Excitation pulses, which are called binomial pulse (e.g., 1-1, 1-2-1, 1-3-3-1), are split, and the phase difference between the resonance frequencies of water and fat is utilized (Fig. 2.14). Each technique has pros and cons (Table 2.3).

2.8 Metallic Artifacts

- Inevitably, a metallic artifact will arise if there is a ferromagnetic component within the human body.
- Staples used in the ACL reconstruction surgery will distort the image due to localized magnetic field inhomogeneity. In this case, characteristic "signal dropout" in the direction of frequency encoding and overlapping of the artifact in a wider range in the phase encoding direction (Fig. 2.10).
- Metallic artifacts are particularly notable with the gradient-recalled echo technique, which is sensitive to magnetic field inhomogeneity.
- Very small metallic particles may be incidentally discovered at MR imaging (Fig. 2.11). Metallic artifacts arising from such small objects are localized to a small area, but one needs to be careful because it can cause a burn injury.

Fig. 2.10 **Metallic artifact**. Status post-ACL reconstruction. (**a**) Surgical stables are observed in the femur and tibia in this lateral knee radiograph. (**b**) On sagittal PDWI, image distortion due to localized magnetic field inhomogeneity (*arrows*) and signal dropout are seen. The phase encoding direction is superior-inferior, while the frequency encoding direction is anterior-posterior. (**c**) Metallic artifacts are particularly notable with the gradient-recalled echo technique, which is sensitive to magnetic field inhomogeneity (coronal T2*WI)

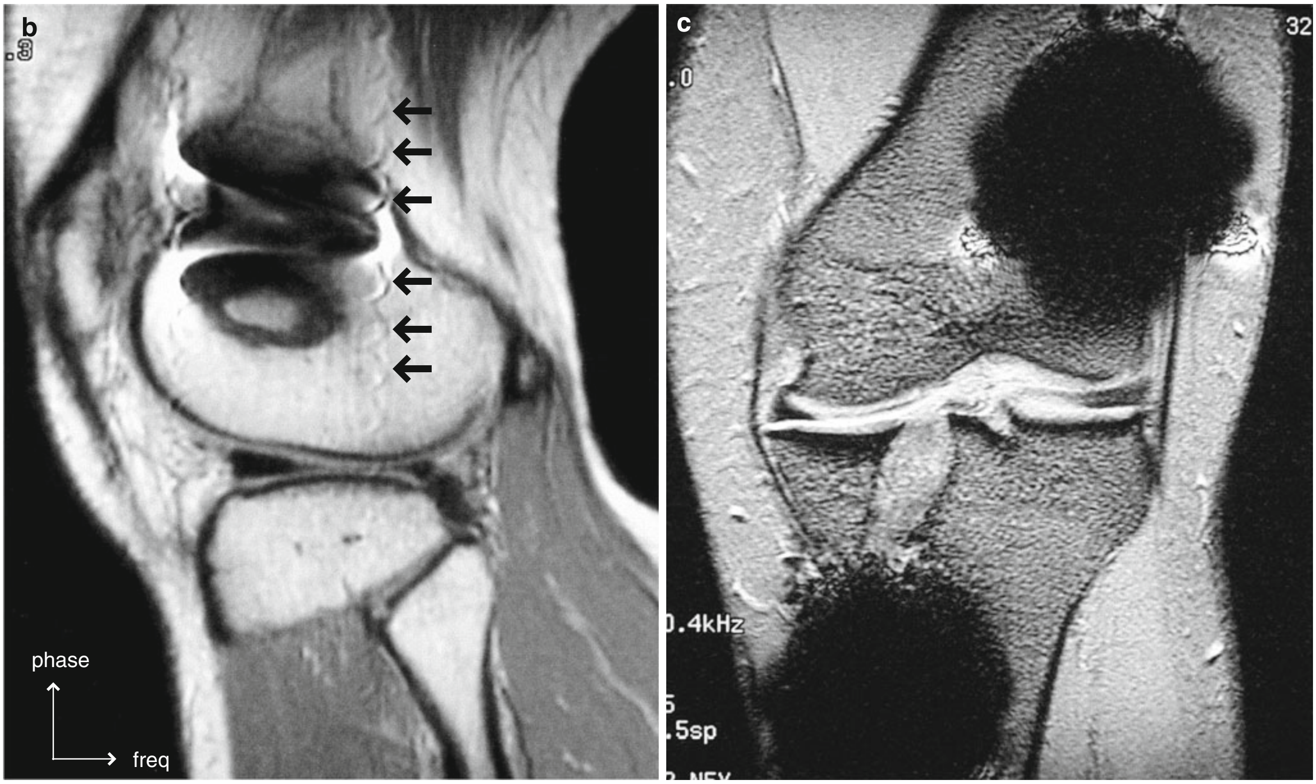

Fig. 2.10 (continued)

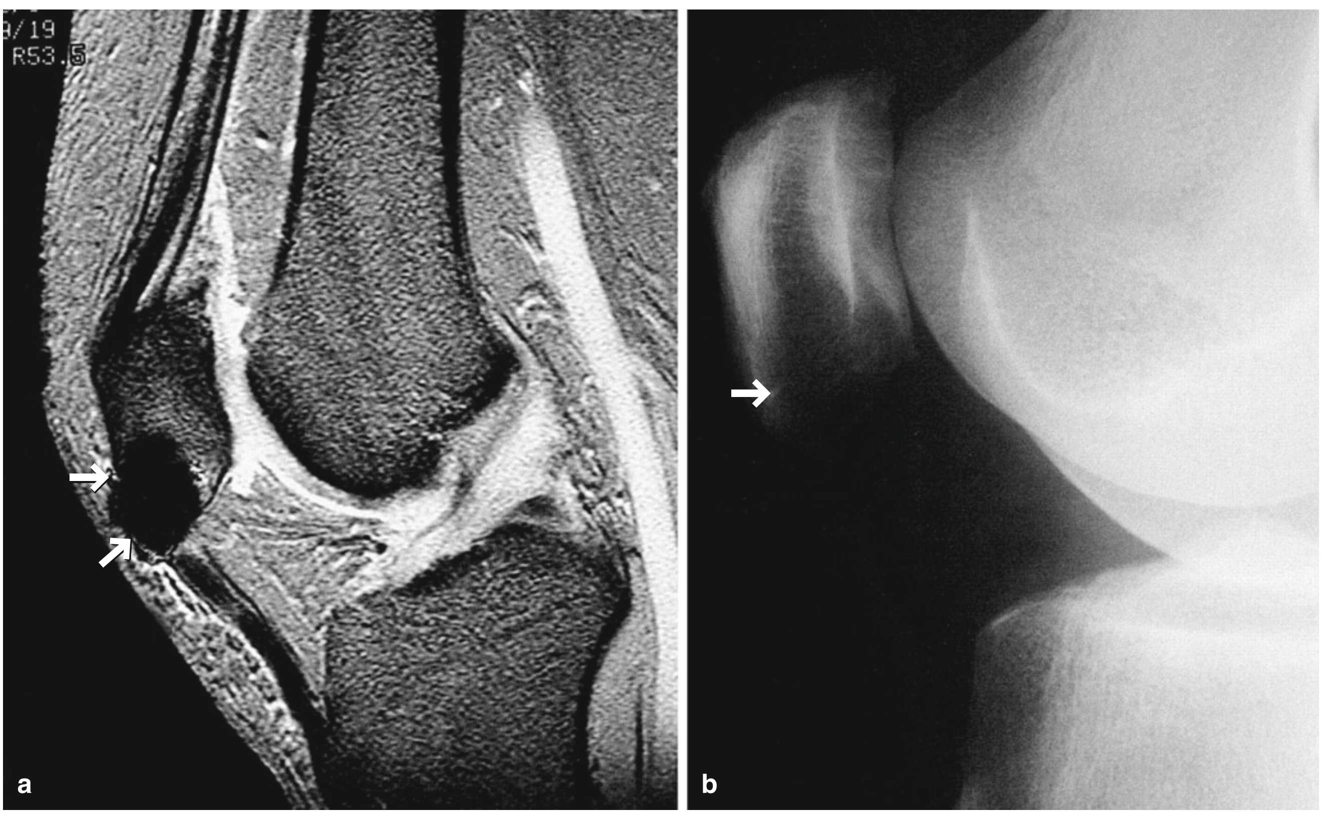

Fig. 2.11 Metallic artifact due to a very small metal particle. (**a**) In this T2*WI, there is a localized signal dropout and image distortion at the inferior aspect of the patella (*arrows*). (**b**) This was due to a very small metal particle (*arrow*) which is just visible on the lateral radiograph

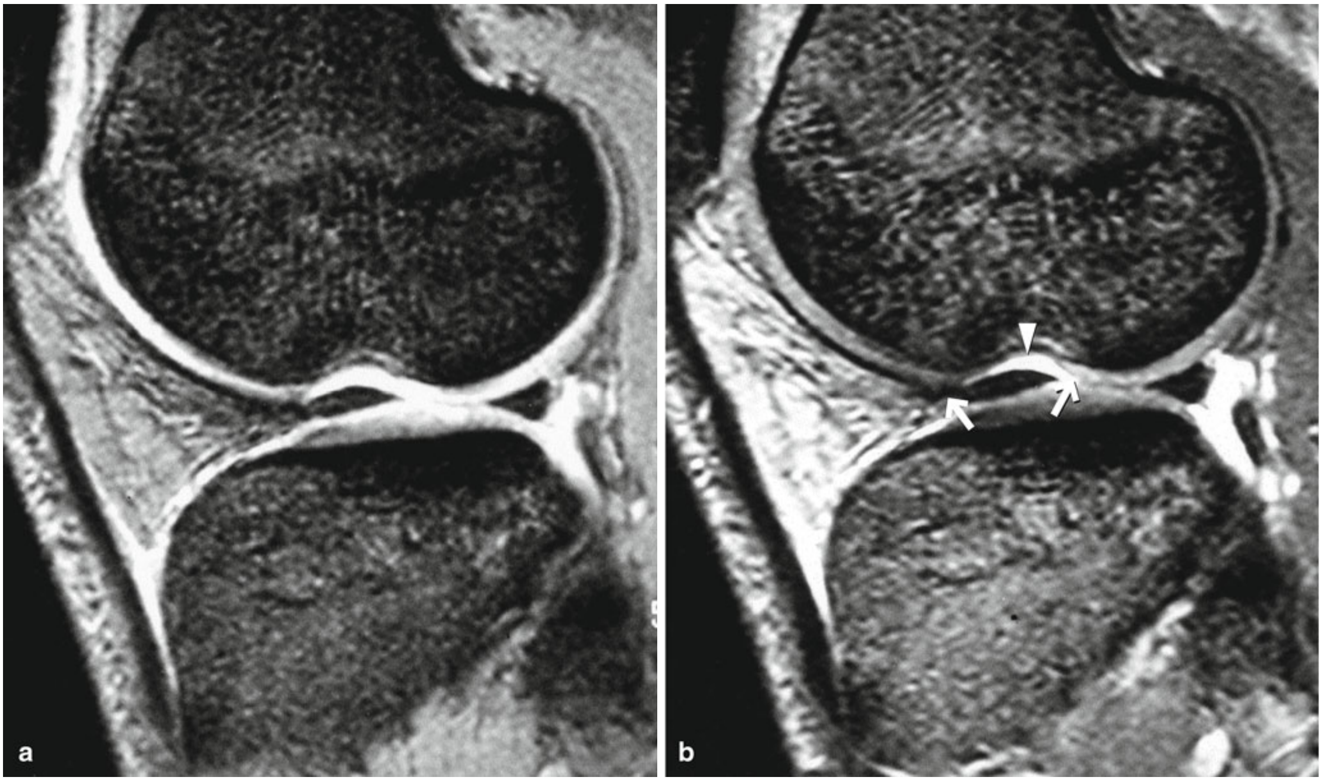

Fig. 2.12 **Delineation of cartilage using the MTC method**. (**a**) T2*WI (GRE, 545/15, flip angle 30°) and (**b**) T2*WI with added MTC (same parameter as **a**). In T2*WI, cartilage and joint fluid are both exhibiting hyperintensity. By addition of MT effect, cartilage signal is specifically suppressed (*arrows*) and improves the contrast against hyperintense joint fluid (*arrowhead*)

2.9 Magnetization Transfer Contrast (MTC) Method, MT Effect

- MRI mostly visualizes protons of free water molecules.
- Other than free water, there are water molecules that are bound to high-molecular-weight proteins, and their resonance frequency ranges a few thousand Hz.
- In MTC method, contrast is created by suppression of signals from free water by irradiating off-resonance pulse (i.e., the pulse that is more than a few thousand Hz away from the resonance frequency of free water molecules).
- MTC method improves the contrast on T2-weighted images between joint fluid and hyaline cartilage, which is mainly composed of collagen and proteoglycan, by specifically suppressing signals from cartilage (Fig. 2.12). However, by irradiating MT pulses:
  1. Heat will be generated in the body as determined by the specific absorption rate (SAR)
  2. Scan time will be slightly prolonged
- FSE techniques that utilize many 180 degree pulses also involve the MT effects

2.10 Imaging Techniques for Cartilage

- The two most commonly used MR sequences for cartilage imaging are the following (Table 2.4) (Fig. 2.13):
- Balanced steady-state free precession (3D balanced gradient echo) technique offers a new method to delineate cartilage and includes sequences such as TrueFISP (Siemens) and Balanced FFE (Philips). Use of a relatively large flip angle leads to depiction of joint fluid as hyperintensity and enables acquisition of high-contrast images. Also, TR can be shortened and thus high-quality cartilage imaging within a short scan time can be achieved.

Table 2.4 Comparison of diagnostic performance of T2-weighted FSE and T1-weighted GRE sequences

	Sensitivity for cartilage defect detection	Specificity for cartilage defect detection
T2-weighted FSE with MTC	94%	99%
Fat-suppressed T1-weighted GRE	75–85%	97%

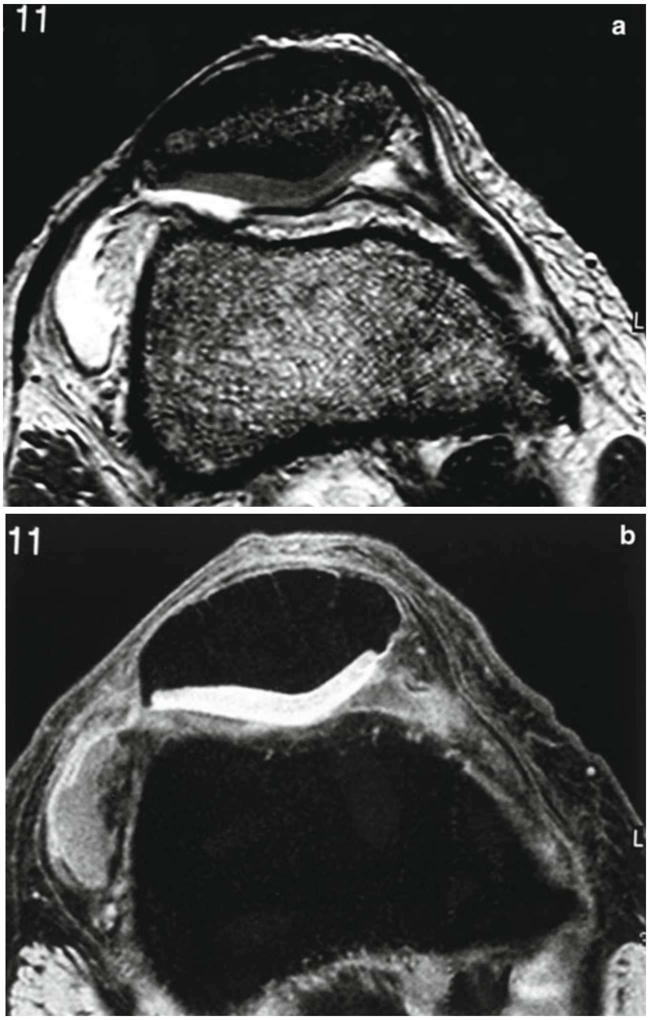

Fig. 2.13 Imaging of hyaline cartilage. In FSE T2WI with MTC (**a**), cartilage appears hypointense in contrast to hyperintense joint fluid. In FS GRE T1WI (**b**), cartilage appears hyperintense. (**a**) FSE T2WI with MTC (TR/TE = 38/14, flip angle 30°, off-resonance MTC, scan time 4 min 32 s). (**b**) FS GRE T1WI (TR/TE = 32/6.8, flip angle 25°, fat suppression, scan time 5 min 03 s). Both were 1.5 mm slice thickness, 130 mm FOV, and 256 x 512 matrix

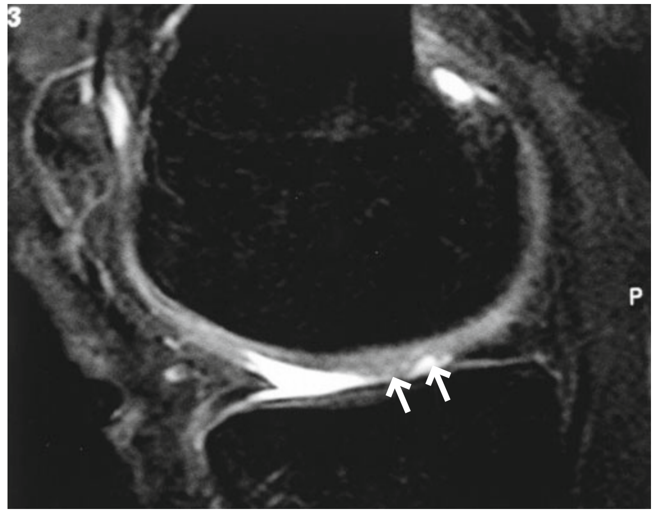

Fig. 2.14 Delineation of cartilage using 3D balanced gradient-echo sequence. Balanced FFE (TR/TE = 12/6.0, flip angle 70°, 1-3-3-1 selective water excitation applied, slice thickness 1.6 mm, FOV 140 mm, matrix 256 × 512, scan time 4 min 06 s). Joint fluid appears hyperintense, creating a good contrast against superficial cartilage damage (*arrow*)

Reference

Disler DG, et al. Fat-suppressed three-dimensional spoiled gradient-echo MR imaging of hyaline cartilage defects in the knee: comparison with standard MR imaging and arthroscopy. AJR. 1996;167:127–32.

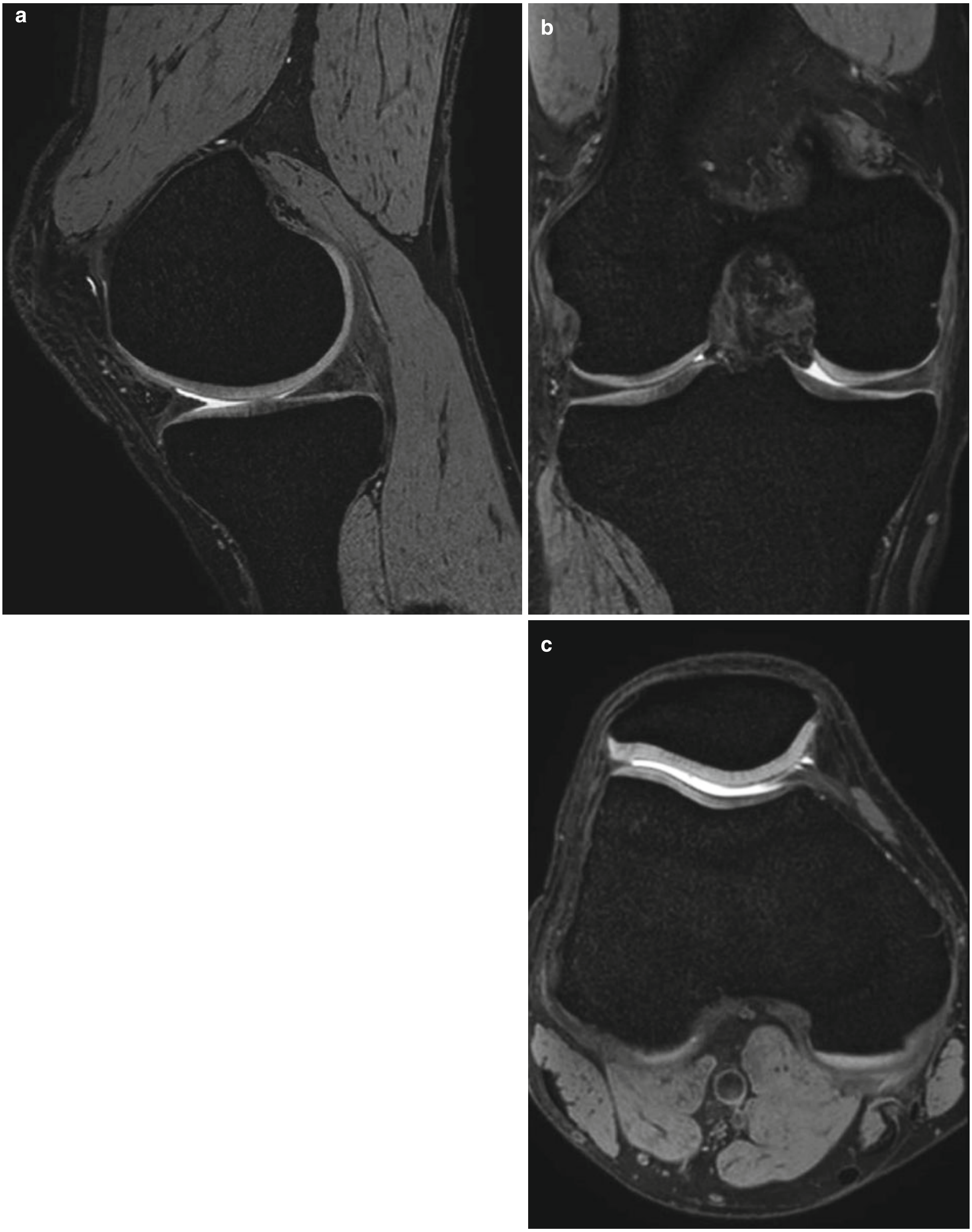

Fig. 2.15 3D FS GRE T2*WI of the knee. (**a**) sagittal (TR/TE = 19/7.0 + 13.3), (**b**) coronal reconstruction image, and (**c**) axial reconstruction image. (**b**) and (**c**) were reconstructed from the sagittal image (260–320 slices, depending on the size of the knee) to enable evaluation of cartilage, menisci, synovium, and intra-articular free bodies

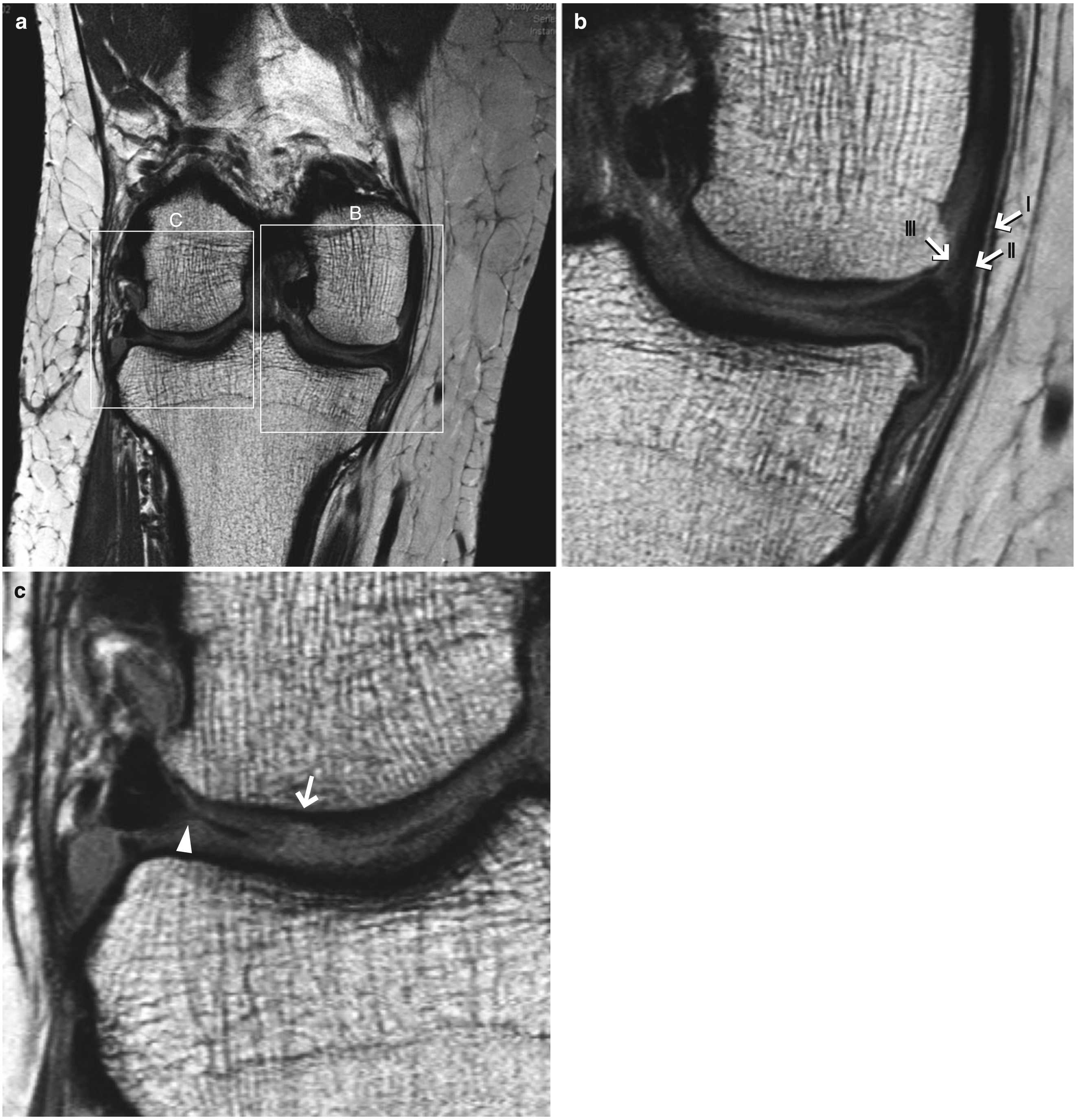

Fig. 2.16 3.0 T MRI of the knee. Coronal image (**a**) and the magnified images (**b** and **c**). (**a**) FSE 2,025/20, 3.0/0.3, FOV 160, matrix 1024 × 1024. (**b**) Magnified image of the medial compartment shows three layers of the medial collateral ligament (I, II, III, *arrows*). The quality of image is equivalent to that offered by high-resolution images acquired using microscopy coil (see Chap. 5, Fig. 5.3). (**c**) Magnified image of the lateral compartment clearly shows focal cartilage defect of the lateral femoral condyle (*arrow*) and distortion of lateral meniscal free edge (*arrow head*)

Advantages and Disadvantage of 3 T MRI

- Improved signal-to-noise ratio:
  - High-resolution image: thin slice thickness, small FOV, 1024 matrix size
  - Shorter scan time, increased acquisition series
- Prolongation of T1 values and slight shortening of T2 values (but this is not a significant disadvantage for knee imaging)
- Chemical shift becomes more notable (and thus adjustment of bandwidth and the use of fat suppression is required)
- Lower RF infiltration, signal inhomogeneity (multichannel, parallel imaging may be needed)
- Increased magnetization effect (increased metal-related artifact, application to susceptibility imaging)
- Increased SAR (beware of excessive heat production)

Reference

Ramnath RR, et al. Accuracy of 3-T MRI using fast spin-echo technique to detect meniscal tears of the knee. AJR. 2006;187:221–5.

Image Acquisition Protocol for the Most of Images Used in This Book

1.5 T

Slice thickness 3.0–3.5 mm, slice gap 0.3–0.5 mm
Sagittal images: 23 slices, coronal and axial images: 18 slices
FOV 140–150 mm, matrix 512 × 256 or 864 × 512

- Intermediate-weighted (close to proton density-weighted, and thus in this book, it will be called "proton density-weighted") FSE: 1,300–2,500/13–17, ET 4–6 (+DRIVE if appropriate).
- Fat-suppressed proton density-weighted images: fat-suppression (e.g., 1-3-3-1 water excitation pulse) is added to the above sequence.
- T2*-weighted image: GRE 500–700/14–15, flip angle 25–35°.
- T2-weighted images: FSE 2,500–3,500/90–100, ET 10–15.
- T1-weighted images (tumors and bone marrow pathologies, only with contrast-enhanced imaging): SE 350–500/11–17.

3.0 T

2D imaging
Slice thickness 2.0–2.5 mm, slice gap 0.2–0.3 mm
Sagittal images: 26–30 slices, coronal and axial images: 26 slices
FOV 150 mm, matrix 864 × 512 or 1024 × 864

- Proton density-weighted FSE: 2,400–2,800/17–30, ET 4–7 (+DRIVE if appropriate).
- Fat-suppressed proton density-weighted images: fat suppression (e.g., 1-3-3-1 water excitation pulse) is added to the above sequence.
- T2-weighted and T1-weighted images: almost identical to 1.5 T imaging.

3D imaging
Slice thickness 0.6 mm/−0.3 mm (overlapping)
Sagittal images: 280 slices, coronal and axial images: reconstructed from the sagittal images, FOV 150 mm, matrix 512 × 512 (0.3 × 0.3 × 0.3 mm isovoxel)

- Fat-suppressed T2*-weighted 3D GRE: 19/7.0 + 13.3 (addition of first echo and second echo), fat suppression (e.g., 1-3-3-1 water excitation pulse)

Abbreviations: *SE* spin echo, *FSE* fast spin echo, *GRE* gradient echo, *ET* echo train length

http://www.springer.com/978-3-642-17892-4

Magnetic Resonance Imaging of the Knee
Niitsu, M.
2013, XX, 204 p., Hardcover
ISBN: 978-3-642-17892-4