Invited Review

The Magic Angle Effect: A Source of Artifact, Determinant of Image Contrast, and Technique for Imaging

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This review provides a formalism for understanding magic angle effects in clinical studies. It involves consideration of the fiber-to-field angle for linear structures such as tendons, ligaments, and peripheral nerves, disc-like and circular structures such as menisci and labra, as well as complex three-dimensional structures. There may be one or more fiber types with different orientations within each of these tissues. The orientation of these fibers to B_0 is crucial in determining their magic angle effect. Tissues may show a variety of appearances depending on their baseline T2, as well as the increase in T2 produced by the magic angle effect. The appearances are affected by TE, which affects both the general tissue signal level and the change in signal produced by the magic angle effect, fiber-to-slice orientation, and partial volume effects. Deliberate positioning of structures and tissues at particular orientations to B_0 can be used to increase the signal from tissues such as tendons and ligaments and so allow them to be imaged with conventional sequences. The technique can also be used to produce contrast between tissues with fibers that have different orientations to B_0.

Key Words: magnetic resonance imaging; magic angle effects; artifact; magic angle imaging; contrast
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IN PULSE SEQUENCES with a moderate or short TE, the signal intensity of tendons and ligaments depends on their orientation to the static magnetic field (B_0) (1–3). These highly ordered, collagen-rich tissues contain water that is bound to collagen. The protons within this water are subject to dipolar interactions whose strength depends on the orientation of the fibers to B_0. These interactions usually result in rapid dephasing of the MR signal after excitation. As a consequence, tendons and ligaments typically produce little or no detectable MR signal and appear dark when imaged with conventional clinical pulse sequences.

The dipolar interactions are modulated by the term $3\cos^2\theta - 1$, where θ is the angle the structures make with the magnetic field B_0. When $3\cos^2\theta - 1 = 0$ ($\theta = 55°$, 125°, etc., approximately, the magic angle), dipolar interactions are minimized with the result that the T2 of these tissues is increased and signal intensity may become evident within them when they are imaged with conventional pulse sequences. The magnitude of the magic angle effect may be quite large. For example, Fullerton et al (1) have described an increase in T2 of Achilles tendon from 0.6 to 22 msec and Henkelman et al (2) have described an increase from 7 to 23 msec when the orientation of the tendon to B_0 was changed from 0° to 55°. With some commonly used pulse sequences this may correspond to the tendon signal intensity increasing from the bottom of the imaging gray scale to the top of it.

In initial studies with clinical MRI the effect was seen principally in tendons that underwent a change of direction along their course such as the supraspinatus tendon near its insertion so that the fibers of one part of the tendon were oriented at or near 55° to B_0. The high signal resulting from the increase in T2 in the part of the tendon at 55° to B_0 simulated an increase in T2 produced by disease, and so the effect was found to be a source of confusion and was regarded as an artifact, which was to be avoided if possible (3,4).

The main method of avoiding magic angle effects was to increase the echo time (TE) of the pulse sequences used to image tendons and ligaments. If the TE of the pulse sequence was increased sufficiently (e.g., to greater than 37 msec for tendons in one study (5), the increase in T2 produced by the magic angle effect did not result in an increase in signal in the tendon or ligament, whereas diseases that increased tissue T2 more than the magic angle effect did, resulting in an increase in signal that could be correctly attributed to disease. While this approach helped with specificity, it could result in a loss of sensitivity for disease that did

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not increase T2 as much as the magic angle effect did. Since the effect produces a relatively large increase in T2, this could be a common occurrence, as noted by Peterfy et al (6) in imaging tears in the meniscus of the knee.

Another way of avoiding diagnostic confusion due to the magic angle effect is to use T1-weighted approaches, which may be more effective in distinguishing effects due to disease from those due to magic angle effects, providing that effects due to the increase in T2 can be minimized. This is because the T1 of tendons and ligaments is not changed, or only slightly changed, by the magic angle effect and changes in T1 due to disease may be quite large. In distinguishing disease from magic angle effects there is also a role for alternative patient positioning, although this may be limited by physical constraints due to the confined space within most MR systems.

Several recent developments have prompted a reconsideration of the role of magic angle effects in clinical practice and have extended its role to other situations besides that of a source of artifact. The more widespread use of vertical static field magnets now means that different orientations of tendons and ligaments to the static magnetic field are seen, in addition to the well-known patterns found with the typical horizontal bore solenoidal magnets, and so magic angle effects are now seen in a wider range of situations. The use of a vertical field magnet may resolve the problem of distinguishing magic angle artifact from degeneration in the supraspinatus tendon, but create difficulty with the infraspinatus tendon, which may display a high signal because fibers are at the magic angle. Open magnets may allow an even wider range of orientations of tissues to B_0, particularly if dynamic studies are being performed, and this may result in magic effects appearing in even more situations.

There has been interest in reducing pulse sequence TEs to times as short as 8–80 μsec (7,8). With these ultrashort TE (UTE) sequences, signal can be detected from tendons, ligaments, and menisci with their fibers at 0° to B_0. These tissues previously gave no signal with conventional sequences except when their fibers were orientated at 55° to B_0. The signals detectable with UTE sequences may vary with orientation to B_0 and the situation may be complicated by the fact that UTE sequences are frequently used with long T2 suppression methods, which may decrease the signal from tissues when their T2 has been increased by the magic angle effect, rather than increase it (8).

There has also been recognition of magic angle effects in a wider range of tissues including peripheral nerve (9) and tissues with short T2s such as the basal layers of articular cartilage and some forms of fibrocartilage in which MR signal has previously been undetectable with conventional pulse sequences, but can now be seen with UTE sequences (8).

While magic angle effects have been described in the posterior root of the lateral meniscus when this tissue is imaged in a typical solenoidal horizontal bore magnet and not elsewhere in the meniscus (6), far more widespread magic angle effects are seen in the meniscus with vertical field magnets. These may involve circumferential, radial, and superficial fibers of the meniscus, which may all be in different orientations to B_0 and produce a variety of different appearances depending on slice orientation, partial volume effects, and other factors. It may be difficult to understand signal intensity and conspicuity of the meniscus in this situation without including an appreciation of magic angle effects. Similar considerations apply to articular cartilage, although magic angle effects in this tissue have been studied in far more detail.

Although emphasis has been placed on orientations of fibers at 55° to B_0 producing an increase in signal relative to the orientation at 0° a loss of signal may be seen in the fibers at 0° relative to the majority of fibers at angles different from 0°. There are also situations in which fibers are oriented in the same general direction but cover a wider or narrower range of angles. High contrast may result between tissues with different angular dispersions of fibers, with structures orientated at or near angles of 55° or 90° relative to B_0.

It has also been possible to deliberately position tendons and ligaments at or near the magic angle to increase their T2 so that signal from them becomes detectable with conventional pulse sequences (10–13). Changes in this signal due to disease, contrast enhancement, or both can then be detected. The available signal also provides access to other MRI parameters such as magnetization transfer and diffusion. In addition the same general approach of purposefully orientating structures or tissues at particular angles to B_0 can be used to produce conspicuity between tissues or components of tissues with fibers oriented in different directions.

In clinical practice it is no longer possible to regard the magic angle effect just as a source of artifact in certain tendons and ligaments that happen to be at 55° to B_0 when these structures are imaged in typical solenoidal magnets. The broader view of the role of magic angle effects includes localized artifacts as first described, but in a wider range of situations, magic angle effects as a major determinant of contrast in tissues such as the menisci and articular cartilage, as well as an imaging technique in applications where detectable signal can be increased such as in disease in tendons (both with and without contrast enhancement) and a method for exploiting differences in fiber direction to develop conspicuity. In this article we elaborate on this concept and provide examples in clinical and research applications.

THE MAGIC ANGLE EFFECT

The structure of collagen and the physical chemistry underlying the magic angle effect are the subject of another article in this issue and are not dealt with in this article, which is concerned with magic angle effects in clinical imaging.

Tissues or structures that have demonstrable magic angle effects with proton MRI are listed in Table 1. A common feature of most tissues in the list is ordered collagen. This includes peripheral nerve, which has collagen in the epineurium, perineurium, and endoneurium. Ordered collagen of this type is not seen in the central nervous system (CNS). Magic angle effects have

Table 1
Tissues or Structures Demonstrating Magic Angle Effects With Proton MR Imaging

Tendons
Ligaments
Entheses
Peripheral nerve
Labra (glenoid and acetabular)
Intervertebral discs
Other discs
Menisci
Fibrocartilage
Articular cartilage
Fasciae, membranes, capsules, bands (variable)
Muscle (uncertain with proton MR imaging)
Cortical bone (uncertain)

been described in muscle with phosphorous spectroscopy (14) but demonstration of these with proton imaging has proved elusive; if they are present they are quite small. There has been one description of magic angle effects in cortical bone samples (15). Although signal can now be detected from cortical bone with UTE imaging techniques, and bone does contain ordered collagen, to date there has been no convincing demonstration of magic angle effects in vivo with MRI.

The imaging demonstration of articular cartilage now includes the deepest layers (calcified layer and deep radial zones) that can be visualized with UTE sequences, and these tissue components display magic angle effects. Likewise, the fibrocartilage present in entheses can now be detected with UTE sequences, and this tissue also displays magic angle effects (16).

The change in signal intensity produced by differences in fiber-to-field orientation provides the characteristic signature of the magic angle effect. The basic pattern of T2 and signal intensity change is shown in Fig. 1. Both T2 and signal intensity are maximal at 55° (and 125°) to B_0 with minimal at 0° and to a lesser extent, 90° to B_0. The width of the peak varies with dispersion of fiber angles to B_0 within tissue. If the fibers are highly parallel, a narrow peak results, but if the fibers are spread over a range of angles, a broader peak is seen.

While the magic angle effect is commonly manifested as a local increase in signal intensity when fibers are oriented at or close to 55° relative to the signal from adjacent fibers at angles greater or lesser than 55°, the effect may also be manifest as a local area of decreased signal intensity when fibers are at 0° or 90° relative to the signal from adjacent fibers at angles greater or lesser than each of these angles.

Although a small change in T1 has been described in some tissues as a result of magic angle effects (2), this is a much smaller than the change in T2 and is usually not significant in the clinical context.

For consistency, we take the T2 and the signal from a collagen-rich tissue with its dominant fibers oriented at zero degrees to B_0 to be the baseline value, and consider situations in which the T2 (and signal intensity) are increased from this level as a result of magic angle effects. A major determinant of this increase is the fiber-to (static) field orientation and this forms the subject of the next section.

FIBER-TO-FIELD ORIENTATION

The signal intensity of a tissue containing ordered collagen depends on a number of factors, beginning with those that determine fiber-to-static field orientation.

Magnet Type and Static Field (B_0) Orientation

The orientation of the patient to B_0 is largely determined by the magnet type with: 1) the long axis of the patient parallel to B_0 in a typical solenoidal magnet; 2) the long axis of the patient perpendicular to B_0 in a vertical field magnet; and 3) variable orientations of the patient to B_0 with (truly) open magnets. Of particular interest in the third case are orientations not achievable, or not easily achievable; such as, in the first two cases, left-right orientation of B_0 relative to the patient. These consid-

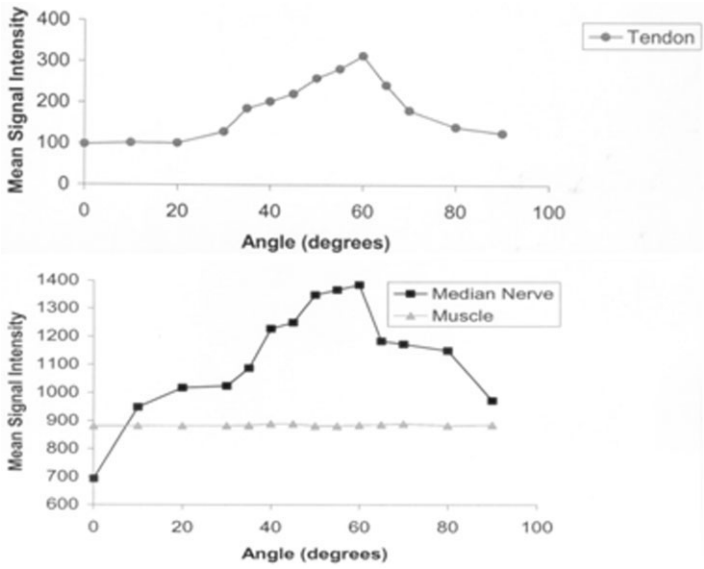

Figure 1. Plot of signal intensity vs. orientation to B_0 for flexor tendons (**a**) and median nerve (**b**). The signal intensity increases up to a maximum at about 55° and decreases toward 90°.

erations generally dictate the macroscopic orientation of structures and tissues, although with the limbs, additional options are available with creative positioning.

It is useful to consider tendons, ligaments, and peripheral nerve, in which the basic orientation of the tissue is essentially linear, as one group of tissues; menisci, labra, intervertebral discs, and some articular cartilage such as the tibial plateau, in which the basic configuration of the tissue is disc-like or circular, as a second group; and articular cartilage in other situations as well as fibrocartilage, in which the tissue geometry is more complex, as a third group. Within these groups tissue fibers may be oriented in a single direction or in multiple directions.

Tissue Structure: Direction and Planes

With tendons, ligaments, and peripheral nerves the macroscopic fiber structure is linear and the orientation of fibers largely follows this pattern. There is some dispersion of fibers at branches as well as at attachments of tendons and ligaments. The direction of tendons may also change at pulleys but the internal fiber orientation follows the direction of the tendon or ligament as a whole.

In the case of knee menisci, which is used to illustrate general principles involved, the following situations are found:

Situation 1. In a typical solenoidal magnet, with the patient horizontal and supine in the bore of the magnet, the plane of the meniscus is perpendicular to B_0.

Situation 2. In a vertical field magnet, with the patient lying horizontal and supine between the pole pieces, the plane of the meniscus is parallel to B_0.

Situation 3. With an open MR system, the plane of the meniscus could be perpendicular to B_0 as in Situation 1, as well as parallel to B_0 with the meniscus oriented anterior to posterior as in Situation 2. However, another possibility is with the patient upright or supine with his or her long axis transverse to the B_0. In this situation, B_0 is parallel to the plane of the meniscus but in a left-right, or medial-lateral, direction rather than the anteroposterior direction.

With articular cartilage, the plane of articular cartilage reflects the underlying bone structure with a disc-like appearance on the tibial plateau, for example, and more complex curved shapes at other sites such as the lower end of the femur.

Fiber Orientation and Type

While collagen fibers vary in size in tendons, they usually have the same general orientation within a predominantly linear structure. In ligaments the orientation is also linear but the fibers may be present in sheets.

Fiber types within the meniscus have been studied for many years, with improved results obtained more recently using scanning electron microscopy (17). This technique shows three distinct layers of organization. 1) A mesh-work of thin fibers of approximately 30 μm in diameter, which covers the surface of the tissue. Beneath this is a superficial, lamella-like layer of collagen fibers to a depth of 150–200 μm, which is predominantly radial in direction. India ink staining shows deviation from the radial orientation at the surface, particularly at the junction of the body and posterior horns of the medial meniscus. 2) The main body of the meniscus, which is composed of predominantly circumferential bundles of collagen fibers with a concentration of these at the roots of the menisci. 3) A smaller proportion of radial fibers (radial ties). In addition, loose connective tissue continuous with the perimeniscal tissue enters the meniscus from its outer margin.

The basic orientation of fibers in articular cartilage is well known, with a calcified layer, deep radial fibers, a transitional layer, and tangential superficial fibers. The radial fibers are generally perpendicular to bone. The radial and tangential fibers are perpendicular, providing a wide range of fiber-to-static field angles.

Fiber-to-Field Orientation

The fiber-to-field orientation is relatively straightforward for tendons, ligaments, and peripheral nerves. For menisci and cartilage, the different planes and fiber orientations result in more complex patterns. In Situation 1 (solenoidal cryomagnet), both the circumferential fibers and the radial ties are generally at 90° to B_0. In Situation 2 (a vertical field magnet), meniscus circumferential fibers are at a range of angles to B_0, including the magic angle. In addition, radial ties are at another set of angles to B_0 some of which include the magic angle (3). With open systems other orientations of fibers to B_0 are possible.

In cartilage the dominant fiber direction is radial with a smaller transitional zone and a thinner superficial zone with tangential fibers. The orientation of the bone provides a guide to the direction of the (perpendicular) radial fibers. At the margins of cartilage, fiber direction may become more parallel to the underlying bone.

BASELINE TISSUE T2 AND OTHER TISSUE PROPERTIES

Baseline Tissue T2

The mean baseline T2 of tendons and ligaments is taken as that with fibers oriented at 0° to B_0 and is in the range of about 2–8 msec, although precise measurements are difficult to obtain and both tissues probably have several short T2 components (8). The majority of these tissues probably show magic angle effects. Peripheral nerve is different in that it has a much longer mean baseline T2 (e.g., 50–60 msec) and only a minority of the tissue is ordered collagen, although this part may produce significant magic angle effects (9).

In tissues with multiple fiber orientations, the baseline T2 is taken as that of the dominant fiber type in a particular region of the tissue. The meniscus as a whole has a T2 or T2* of about 6–8 msec (18). No significant susceptibility effects are thought to be present in the meniscus. With conventional spin-echo sequences with TEs of 10–20 msec, most if not all the signal decays to noise level by the time the receive mode of the MR

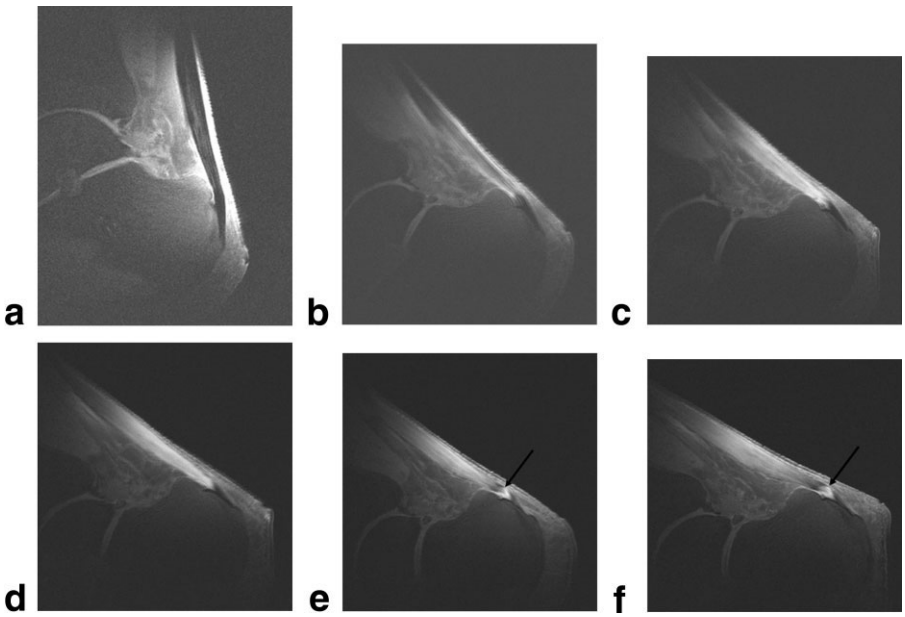

Figure 2. Achilles tendon at 10° (**a**), 30° (**b**), 40° (**c**), 50° (**d**), and 60° (**e**) to B_0. The signal intensity increases with angle in the midtendon region. Contrast is developed around the sesamoid fibrocartilage (arrow).

system is enabled. Loose connective tissue has a longer T2, probably with a value similar to the values of 14–15 msec found for perimeniscal tissue (18). The measured T2 of fibrofatty tissue may be shorter than its T2 because of phase differences between signals from protons in water and those from protons in fat producing signal interference effects. Articular cartilage has a range of baseline T2s of about 1–10 msec for the deep layers up to 30–40 msec for the more superficial layers.

Increase in T2 Due to Magic Angle Effects

Magic angle effects results in an increase in T2 from that seen with fibers oriented to B_0. The dependence of T2 on fiber orientation to magnetic field for highly-ordered, linearly-oriented collagen-rich tissues such as tendon and ligaments is shown in Figs. 1 and 2. T2 has a baseline value at 0°, reaches a maximum at 55°, decreases toward 90° then increases again to a peak at 125°. This peak has the same magnitude as that at 55° and drops down again to the baseline value at 180°. The shape of the curve depends on the fiber type, size, and properties, as well as the detail of fiber orientation within a tissue. Highly parallel fibers showed narrow peaks, while tissue with a wider spread of orientations showed a broader peak. The relative increase in T2 tends to be greater for short T2 than in longer T2 components of tissues, which have a range of T2s similar to articular cartilage. The effect of the increase of T2 on signal intensity depends on the pulse sequence, and in particular, TE (see below).

T1

The values of T1 for tendons and ligaments at 1.5T are in the range of 350–450 msec at 1.5T but because of the low signal available with conventional sequences there is a dearth of clinical data. It is assumed that T1 values of other similar connective tissues are in the same range as tendons and ligaments, and that as with other tissues magic angle effects change T2 but have little effect on T1 (2). The conspicuity of a tissue displaying a magic angle effect may vary depending on the T1 of the tissue and the T1-dependence of the sequence used to examine it.

Other Tissue MR Properties

The mobile proton density of the meniscus is linked to its T2 and is probably less than that of soft tissues. By analogy with articular cartilage, significant magnetization transfer effects would be expected. There are particular difficulties with diffusion-weighted techniques using pulsed gradients for imaging short T2 tissues. The gradient pulses are typically of significant duration and result in TEs of 50–100 msec for b-values in the 500–1000 second/mm^2 range. This is too long to detect signal from short T2 tissues. Diffusion may be limited by the partial binding of water to collagen, which may also make it less easy to detect. On the other hand some anisotropic behavior may be expected as a result of the asymmetric fiber structure of these tissues. Diffusion may be accessible in tissues with longer T2s such as the peripheral nerve and the more superficial layers of articular cartilage. It can also be accessed when the T2s of tissues such as tendons and ligaments are increased by placing them at the magic angle (see below).

TE AND OTHER MACHINE FACTORS

TE

TEs can be grouped in to ultrashort short, moderate, long, and ultralong. The signal intensity detected with tendons and ligaments with their fibers parallel to B_0 is a very low or zero with TEs of 10 msec or longer. These tissues typically showed moderate or high signal with ultrashort UTE sequences even with their fibers at 0° to B_0.

Not only does TE effect the general signal level of the meniscus signal but it also modulates the signal intensity produced by magic angle effects. In general, magic

angle effects are absent at long and ultralong TEs, become more obvious with moderate and short TEs and are reduced with ultrashort TEs. With UTE sequences, subtraction of later echo images from the first image (which is used to reduce the signal from long T2 tissues) may lead to different effects. If as a result of magic angle effects the tissue T2 is prolonged and the TE of the subsequent echo image is not too long, the subtraction image will show low signal. If the TE of the later echo image is prolonged but the signal decays rapidly relative to TE, the signal on the subtraction image may be high.

TR, Flip Angle, and T1

These sequence parameters effect the T1-dependence of the signal. In general, with gradient and spin-echo sequences T1-dependent contrast is maximized when TR is about the same as the T1 of the tissues to be distinguished. Increasing the flip angle within the range of 0–90 degrees generally increases T1 dependence and decreasing the flip angle reduces it. The T1 of short T2 components in tissue may differ from that of long T2 components and if the short T2 components become detectable as a result of magic angle effects, this may produce differences in conspicuity.

In attempting to achieve T1 weighting, inversion pulses may be used. When the length of the inversion pulse is the same order as T2 or longer, the magnetization may not be inverted and the tissue may be saturated. If the T2 of the tissue is prolonged by magic angle effects, then its magnetization may be inverted, producing different T1-dependent contrast.

Other Pulse Sequence Parameters

It is possible that off-resonance fat suppression pulses may partially saturate the short T2 components in the meniscus and reduce their signal. This may produce increased contrast between fibers at the magic angle (longer T2s), which are minimally affected, and fibers at other angles (shorter T2s), which may be more affected.

Other Hardware

Hardware effects such as the nonuniform receiver field associated with surface coils may alter signal intensity in well-recognized ways.

GEOMETRIC FACTORS

Slice Orientation

The position of the slice, whether relative to whole body (sagittal, coronal, or axial) or related to the shape of the tissue of interest, produces characteristic appearances with planar imaging.

Partial Volume Effects

General

Partial volume effects occur when two or more fluids or tissues with different signal intensities partly occupy a voxel and produce in that voxel signal intensity that is intermediate between the two. A boundary between the two tissues or fluids is present within the voxel. The effect may occur in-plane, which is usually the smaller voxel dimension, through-plane (the slice thickness), which is usually a larger voxel dimension with conventional two-dimensional (2D) imaging, or as a combination of these. The partial volume effect may occur within the tissue such as at a boundary between a blood vessel and tissue parenchyma, or at the external margin of a tissue or organ.

Fibers

Partial volume effects involving fibers such as those in the nervous system, tendons, ligaments, and menisci have some more specific features. The tissue fibers may be surrounded by nonfibrous tissue or other fibers at the same or different orientations. The fibers are asymmetric, with long and short axes. The relative dimensions of fibers or groups of fibers are often similar to those of voxels used in MRI. Fibrous tissues may show a characteristic fascicular or punctate pattern when the fibers are oriented at or near 90° to the slice plane, but this pattern is readily lost as the fiber orientation moves away from 90° (19). At the other extreme, through-plane fibers may show high signal intensity if the slice thickness is low and their direction is parallel to the image plane. Loss of these conditions leads to a loss of visualization of the fiber pattern.

Magic Angle Effects

In addition to fiber-to-slice considerations described above, the signal intensity of the fibers may show magic angle effects, i.e., fiber-to-field dependency. This does not occur with nerve fibers within the CNS, but it occurs in the perineurium and endoneurium of peripheral nerves (which contain collagen), and in tendons and ligaments. It may occur more for fibers than endotenon, resulting in a loss of fascicular definition.

In the particular case of meniscus, fiber-to-field dependency occurs in circumferential fibers and radial ties but to a lesser degree in superficial fibers and may be small in the multidirectional small-fiber matrix. The fact that two or more sets of fibers, and in particular, circumferential and radial fibers, produce different signal intensities at different orientations to B_0 has potential for a wide range of different conspicuities between the fibers.

External partial volume effects occur at the boundary between the meniscus and perimeniscal tissue and at the boundary between the external surface of the meniscus and joint fluid. The meniscus is subject to the distinctive features associated with fibers and magic angle effects, but the perimeniscal tissue and joint fluid are not. Joint fluid has a long T1 and T2 and its signal intensity relative to the meniscus varies with T1-weighted sequences (low signal) or proton density–weighted or T2-weighted sequences (higher signal). The perimeniscal tissue has a longer T2 and is of higher signal intensity.

CONTRAST ENHANCEMENT

Contrast enhancement depends on the tissue, the pulse sequence, geometric factors, and the contrast

agent. The patterns vary with the tissue, pulse sequence, and contrast agent. The meniscus is an interesting example because it has a vascular peripheral red zone and an avascular central white zone. It is surrounded by vascular perimeniscal connective tissue. The meniscus has a short T2 and signal has not been detectable with conventional sequences after enhancement. By use of magic angle effects, UTE sequences, or both, signals can be detected in the meniscus and increase can been seen after enhancement. UTE sequences are usefully combined with subtraction since this suppresses the signal from the more vascular perimeniscal tissue (18). In studies with a gadolinium chelate to date, a nonionic agent was used with a high concentration (0.3 mmol/kg) to increase enhancement. This allowed the red zone to be visualized separately from the white zone though increased signal was measured in this zone. This is probably due to diffusion of contrast agent from the red zone or joint fluid.

NORMAL APPEARANCES

These can be seen as an interplay between the following: 1) Fiber-to-field orientation and magic angle effects. 2) T2 (both baseline and increased T2 caused by the magic angle effect) and TE, which determines both the general signal level of the tissue (shorter TE leads to a higher signal level) and modulates the signal produced by the magic angle effect. 3) T1 and TR, flip angle, and inversion time (TI). The T1 of most tissues of interest is moderately short and does not vary with magic angle effect. 4) Other tissue properties and sequence parameters. These have been largely unexplored, but susceptibility effects with gradient echo sequences may be important with calcification. 5) Slice orientation, which determines the basic configuration of the tissue, and partial volume effects. These reflect general principles but the fiber structure is anisotropic and may match the anisotropic shape of voxels. These may show a fascicular type of pattern when fibers are perpendicular to the slice and a linear pattern when fibers are parallel to the slice as well as a nonspecific appearance at intermediate angles. Partial volume effects are modulated by magic angle effects, which effect the signal intensity of the fibers involved. 6) Contrast enhancement, as outline above.

APPEARANCE IN DISEASE

Changes in morphology including size, shape, and position may be diagnostic but this article is primarily concerned with changes in signal intensity. In general, there are two approaches. In the first, the background signal is low or kept low by the use of a sufficiently long TE and abnormalities are recognized as an increase in signal intensity. There is a risk that the TE necessary to keep the background low by suppressing magic angle effects will result in a low signal and that small increases in T2 will not be detectable.

The second approach is to achieve a detectable signal level using a shorter TE with the options to manipulate it by use of sequence parameters and to recognize changes in signal due to differences in relaxation times and other tissue properties. This gives the additional option of recognizing disease processes that reduce signal intensity.

Degenerative changes are typically associated with an increase in T2. If there is overt fluid the T2 may be longer and be best shown with longer TR sequences, which reduce T1 effects. Calcification generally produces a reduction in signal intensity due to low mobile proton density, short T2, and susceptibility effects. It may also be associated with a decrease in T1 (20). Some forms of calcification show an increase in T2 with a decrease in T1, which may lead to an increase in signal intensity with T1-weighted sequences.

Crystal deposition disease is associated with both a low signal and an increase in T2. Fibrosis and scar formation may be associated with a mild increase in T2 in the initial stages, but a reduction in T2 later. Other pathologic processes are also of interest. In the intervertebral discs, desiccation is associated with a reduction in T2 and it is possible that a similar process may occur in other tissues such as tendons and ligaments, but this has not been recognizable using low signal approaches. It may be observable if the tissue is placed at the magic angle.

Loss of order in collagen could result in an increase in T2 and of loss of magic angle effect (i.e., a reduction in the change of signal with shift of orientation from, for example, 0 to 55 degrees.)

MEASURMENTS

Measurements of T2 depend on the range of TEs used to detect signal. Tendons, ligaments, and menisci requires sequences with TEs in the short and ultrashort range for both T2 and T2*. The measurement of T1 is also dependent on the TE of the sequence since this defines what tissues contribute signal. If TE is relatively long, only part of the tissue may contribute signal.

Although there has been some work on diffusion-weighted sequences suitable for short T2 tissues (21,22), these sequences may be difficult to implement on clinical MR systems. If magic angle effects are used to prolong T2, the diffusion weighting is only for fibers with signal in the detectable range.

ARTIFACTS

Artifacts are the most widely recognized manifestation of magic angle effects and are typically recognized on solenoidal magnets as a localized region of signal intensity in a tendon or ligament undergoing a change in direction, as with the supraspinatus tendon and tendons posterior to the medial and lateral malleoli (3,4).

Not so well recognized are areas of increased signal in peripheral nerves due to magic angle effects (9). The roots, cords, and nerves of the brachial plexuses as a whole are generally at about 55° to B_0 when patients are examined in typical horizontal bore cryomagnets. This produces an increase in signal relative to nerves at 0° and also relative to skeletal muscle, which is usually taken as a reference for signal level of peripheral nerve. With typical fat-suppressed T2-weighted or short-tau inversion recovery (STIR) sequences normal nerve sig-

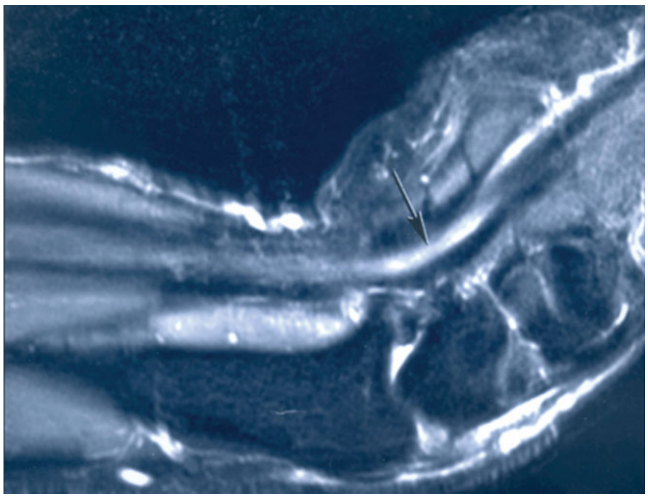

Figure 3. Median nerve. Sagittal T1-weighted spin-echo image. The signal for the nerve is increased at 55° to B_0.

nal is generally less than or equal to muscle signal. If this rule is applied, the whole brachial plexus may appear to have an elevated signal intensity. In addition, the rule of increasing TE (e.g., to greater than 37 msec) to avoid detecting the signal increase due to magic angle effects in tendons does not apply to nerves.

In addition to these difficulties, provocative testing has been recommended for increasing the sensitivity of MR neurography to changes in carpal tunnel syndrome (23,24). This is performed by flexing or extending the wrist but this maneuver may result in a localized increase in signal in the region of the carpal tunnel as a result of magic angle effects (Fig. 3). Likewise, it has been suggested that the elbow should be examined in flexion to detect ulnar nerve entrapment but this can also result in an unwanted increase in signal intensity in the region of clinical suspicion (25).

With typical STIR sequences at the wrist, the median nerve may show visible magic angle effects when the surrounding flexor tendons do not. This is particularly evident with larger TEs. The T1-dependent approaches for distinguishing magic angle effects from disease require the use of short TE or UTE sequences to minimize the T2 dependence of the sequence and may require a short inversion pulse to fully invert the tendon or ligament magnetization. Contrast enhancement may also help if there is a focal area of enhancement.

MAGIC ANGLE EFFECTS AS A DETERMINANT OF IMAGE CONTRAST

This section includes the more complex situations in which the tissue as a whole is at different orientations to B_0 and contains fibers at different orientations to one another. The examples discussed here are the meniscus of the knee, labra, and articular cartilage.

The Meniscus of the Knee

In general, magic angle effects are minimized with the common orientation of the knee in a solenoidal magnet since both circumferential and radial fibers are at 90° to B_0. As a result, magic angle contrast between them is minimized in this situation. The lateral meniscus root fibers may be at 55° and give a high signal. The superficial fibers are at a variety of angles and this may produce a signal with low magic angle dependence.

The patterns with a vertical field are much more variable; circumferential fibers may be at the magic angle, while radial fibers are far from the magic angle and vice versa (Fig. 4). The appearances may vary in a given slice and partial volume effects may result in different appearances when the image slice orientation is changed. The contrast with disease varies. For example chronic calcification has a generally lower signal intensity than either fibers examined with a UTE sequence or fibers at the magic angle.

Labra

The glenoid and acetabular labra show features in common with the menisci, with predominantly circumferential fibers following the bony attachment. These display magic angle effects (26) and produce patterns that vary with B_0, TE, slice orientation, and other factors, as outlined previously.

Articular Cartilage

Magic angle effects are readily seen in articular cartilage and have been the subject of extensive and detailed

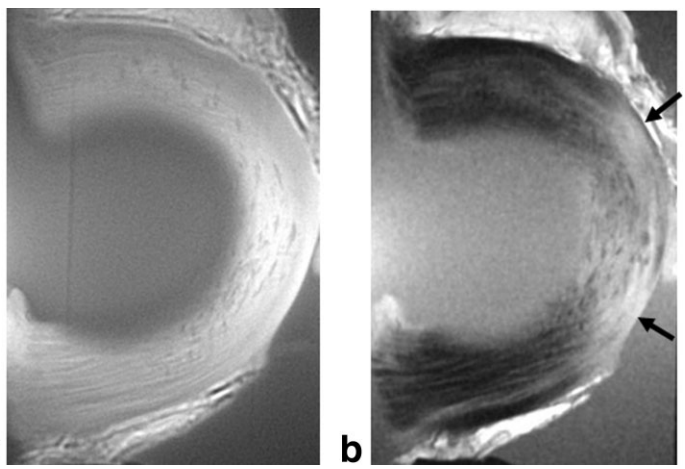

Figure 4. Meniscus. UTE image (**a**) and conventional T1-weighted spin-echo (**b**) with vertical B_0. The UTE image shows high signal (with lower signal from calcification). The conventional spin-echo image shows a marked magic angle effect.

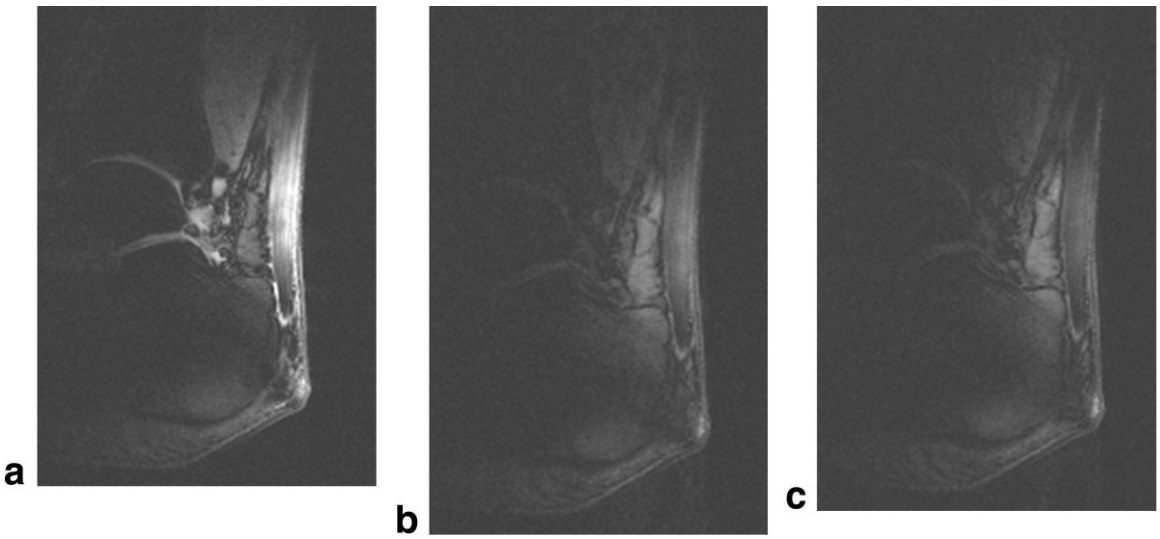

Figure 5. Diffusion-weighted imaging of the Achilles tendon. b = 0 second/mm^2 image (**a**), AP sensitization (b = 500 second/mm^2) image (**b**), and superior-inferior sensitization (b = 500 second/mm^2) image (**c**). There is a similar reduction in signal intensity in the diffusion-weighted images.

study (Figs. 6 and 8) (27–31). The baseline T2 of articular cartilage varies from deep to superficial. In relative terms, greater magic angle effects may be seen with the deep-layer short T2 components. The calcified layer of cartilage has a short T1 and this may lead to high signal from it. Techniques using long T2 reduction to highlight the deep layers of cartilage may reduce its signal intensity when its T2 is increased by magic angle effects.

MAGIC ANGLE IMAGING

By deliberately placing tendons and ligaments at or near the magic angle, increased signal may be seen within them. This provides an opportunity to measure T1 and T2 and to detect effects due to increases or decreases in these parameters that may not otherwise be apparent. It is best suited to linear structures with a single dominant fiber orientation such as tendons, ligaments, and nerves.

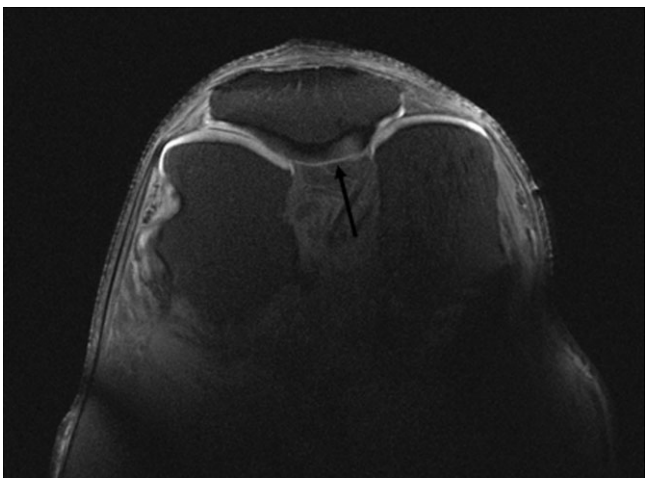

Figure 6. Articular cartilage. The radial fibers are at 0° and the transverse fibers (arrow) are at 90° to B_0.

When signal is detectable it is also possible to assess magnetization transfer effects. The magic angle effects create a free pool that allows indirect access to the shorter T2 components. There is also scope to study other effects such as T1 in the rotating frame. Contrast enhancement is detectable with tendons at the magic angle and more marked and more prolonged enhancement has been identified in Achilles tendinopathy using this technique (11–13). It has also been used to access diffusion. Preliminary studies have shown only a relatively mild degree of anisotropy in spite of the very asymmetric structure of the tendon. This may reflect binding of water to collagen and limited mobility. The appearances are dependent on fiber-to-gradient field orientation (diffusion) as well as fiber-to-static field and fiber-to-slice orientation (Fig. 5).

By placing articular cartilage with the radial fibers at 0° to B_0 contrast may be developed with tangential fibers at 90° to B_0 (Fig. 5). Entheses are a particular application of magic angle imaging in which positioning is used to differentiate tissues with different fiber orientations. To demonstrate sesamoid fibrocartilage it is useful to place tendons near the magic angle so that the signal from the very linear tendon fibers is low but that from the less linear (basket-weave) fibers of fibrocartilage is not reduced to the same degree because the fibers are spread over a much wider range of angles and a significant proportion may be at or close to the magic angle even when the bulk of the tendon fibers are at 10 or more degrees from this angle (Fig. 2). In addition UTE sequences can be used with magic angle imaging to increase signal (Fig. 7) to demonstrate enthesis fibrocartilage exploiting the fact that the fibers of this tissue are largely orientated

perpendicular to the bone to which they are attached. (Fig. 8).

SUMMARY

For a long period, the magic angle effect has been consigned to the dustbin of MR history. It is manifest as an unwanted increase in signal intensity of tendons and ligaments that happen to be at 55° to B_0. It is usually regarded as an artifact and most of the technical effort in relation to it has been spent on avoiding it, or if this was not possible, distinguishing its results from those due to disease.

This review discusses various different tissues in which magic angle effects may be seen and provides a formalism for relating the magic angle effects to the type of magnet the patient is examined in, the macroscopic structure of the tissue under study, and the fiber direction or directions within the tissue. The signal intensity seen in the tissues of interest also depends on the baseline T2 of the tissue and the increase in T2 produced by the magic angle effect. The signal is affected by the TE of the sequence, which sets the general level of signal for the tissue and determines the size of signal change produced by the magic angle effect.

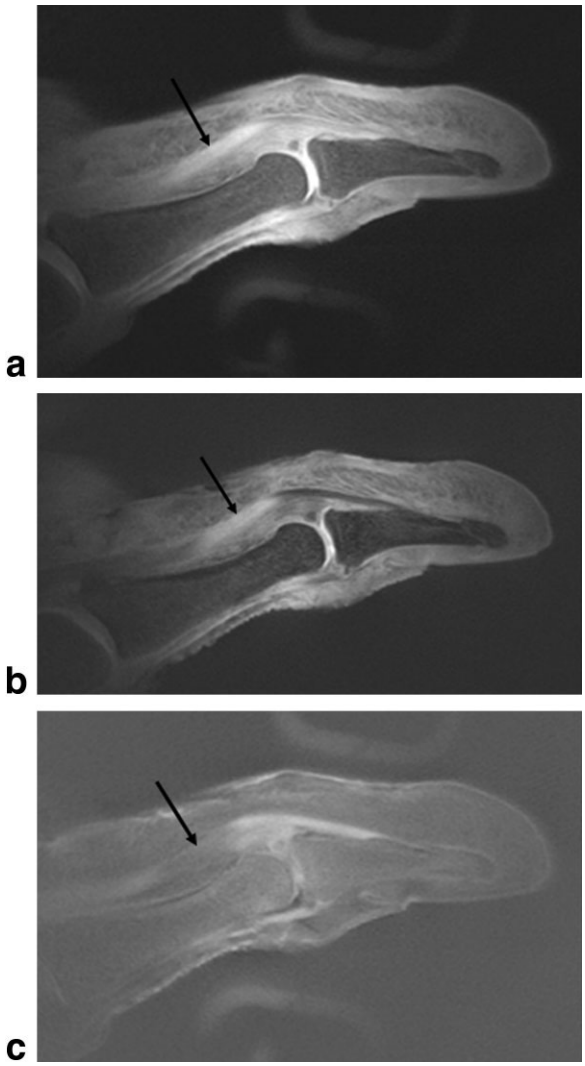

Figure 7. Flexor tendon of the thumb with proximal component at the magic angle. UTE image (**a**), longer echo (**b**), subtraction image (**c**). Higher signal is seen on the UTE image from the part of the tendon at the magic angle (arrow). The signal is also higher on the longer echo image due to its long T2, but it is low on the difference image in (c).

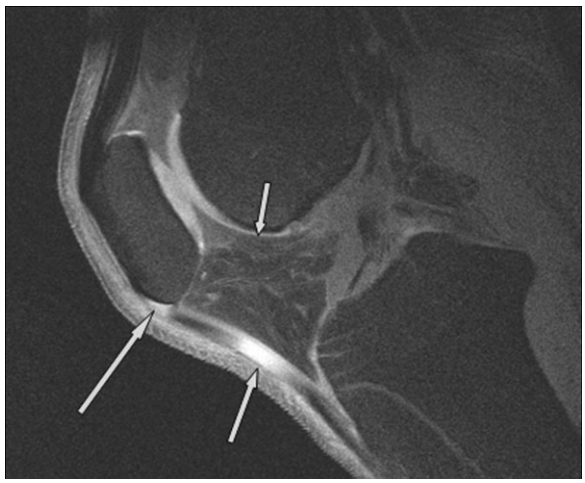

Figure 8. Sagittal signal of lower end of femur and patella tendon. High signal is seen from magic angle effects in the midtendon (medium arrow) and at the enthesis (long arrow). The superficial zone of the articular cartilage is seen (short arrow) but the signal in the radial zone in this region is low and is not seen.

Partial volume effects of fibers may produce fascicular or linear patterns or an indeterminate appearance. These appearances are affected by the magic angle effect as well as the fiber-to-slice orientation.

By deliberately placing tendons and ligaments at or near the magic angle, signal may be generated within them with conventional sequences and this allows study of T1 and T2, contrast enhancement, magnetization transfer, and diffusion. Magic angle imaging may also be used to generate contrast between fibers at different orientations in the same or different tissues.

It is now possible to take a broader view of the magic angle effect and regard it not only as a source of unwanted artifacts, but also as a major determinant of image contrast and an imaging technique.

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