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# The "Magic Angle" Effect: Background Physics and Clinical Relevance[1]

MAGNETIC resonance (MR) imaging signal intensity is primarily determined by intrinsic factors (T1 relaxation time, T2 relaxation time, proton density, flow, susceptibility effects) and extrinsic (operator-selectable) parameters (repetition time [TR], echo time [TE], and flip angle). Structures with freely mobile protons undergo rapid tumbling, which tends to average out dipole-dipole (internuclear) interactions that otherwise can substantially shorten the T2 relaxation time and consequently reduce signal intensity. Tissues that exhibit highly ordered structure, however, restrict the motion and orientation of water protons. Observed signal intensity in these tissues is dependent on yet another factor, the orientation of the tissue in relation to the constant magnetic induction field ($B_0$).

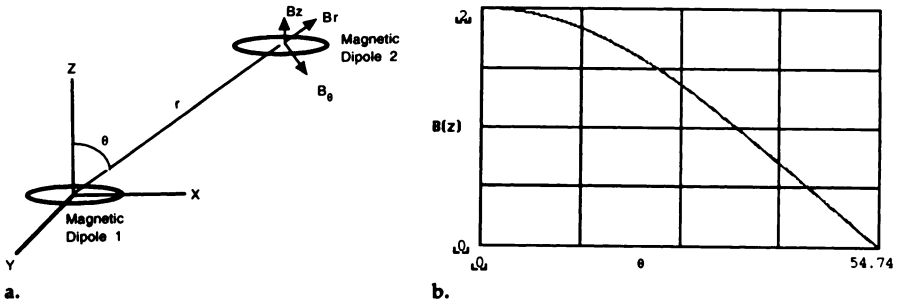


**Figure 1.** Diagrams explaining physics of magic angle effect. **(a)** Dipole-dipole interaction modeled simply as interaction of two current loops (here referred to as dipole 1 and dipole 2). Notice that the dipoles are aligned with $B_\theta$ (z axis). $\theta$ = the angle between the z axis and the vector between the dipoles, $r$ = distance between spins. **(b)** Graph shows magnitude of interaction between dipoles. Notice that $B_z$ goes through 0 at the "magic" angle of 54.74°. The dipolar interaction therefore vanishes at this angle.

## BACKGROUND PHYSICS

One of the principal problems with solids spectroscopy is short T2 times, which are attributed to restricted molecular mobility (1,2). Discovery of angle-dependent T2 values proved a breakthrough in the field of solids spectroscopy because signal intensity of specimens could be greatly augmented by orienting the specimens optimally in relation to $B_0$. The dipolar interaction of two spins can be modeled simply as the interaction of two current loops, which we will call dipoles 1 and 2 (Fig 1). Like the spins, these current loops are assumed to be parallel to the z axis (that is, the aligning field of the magnet). The level of interaction between spins or dipoles can be found by calculating the z component of the magnetic field of dipole 1 and the position of dipole 2. As Eyges stated in "The Classical Electromagnetic Field" (3): $B_r = 2m\cos\theta/r^3$ is the radially directed component of the field, while $B_\theta = m\sin\theta/r_3$, where $r$ is the distance between spins and $m$ is the magnetic dipole moment. The interaction is defined by the Z component of $B$: $B_z = (B_r)\cos\theta - (B_\theta)\sin\theta$ and therefore $B_z = m/r^3 \cdot (3\cos^2\theta - 1)$.

The dipolar interaction between two nuclei scales is $(3\cos^2\theta - 1)$, where $\theta$ is the angle between the internuclear vector joining the nuclei and $B_0$. This dipolar interaction, which tends to reduce signal intensity, disappears when the term $(3\cos^2\theta - 1) = 0$, a condition satisfied when $\theta$ equals 54.74°. This angle, which is commonly rounded to 55°, is referred to as the "magic angle" (1). Magic angle spinning is performed by rotating the sample of interest along an axis equal to the magic angle. T2 decay is greatly retarded, resulting in improved signal intensity.

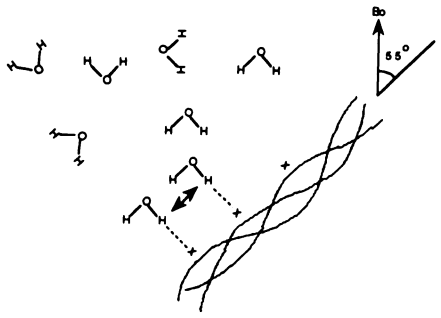


**Figure 2.** Diagram shows bonding between collagen triple helix and proton dipoles. Notice that the proton interaction (arrows) occurs along the same axis as the collagen fiber. When the collagen fiber is oriented approximately 55° in relation to $B_0$, the dipolar interaction falls to 0 and signal intensity is maximal.

## COLLAGEN STRUCTURE

Collagen comprises about one-third of human protein and is an important constituent of tendons, ligaments, retinacula, aponeuroses, cartilage, and bone (4–7). Collagen microfibrils are composed of tropocollagen, which is a protein consisting of three polypeptide chains arranged in a triple helix. The microfibrils are organized into fibers, which are embedded into an amorphous ground substance. The fibers are oriented in parallel bundles, resulting in a highly ordered structure (structural anisotropy). As a result, the motion of water molecules binding to collagenous tissue is greatly restricted, which greatly enhances dipole-dipole interaction. Collagen-containing tissues are particularly prone to magic angle effects (Fig 2) and form the basis of the remaining discussion.

## MR IMAGING CHARACTERISTICS OF COLLAGENOUS TISSUES

### Tendons

Tendons are composed of type I collagen, which is the most prevalent collagen class. Its fibers show highly ordered structure manifested by prominent

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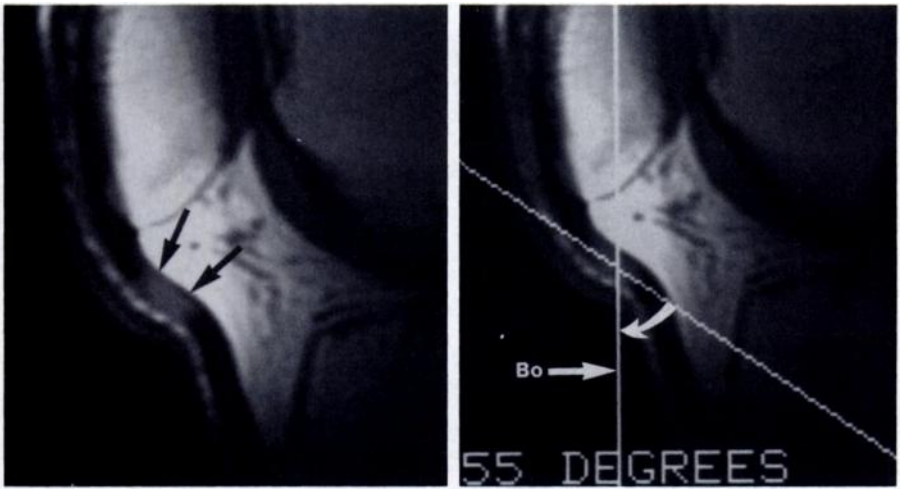
See also the article by Rubenstein et al (pp 219–226) in this issue.




a. b.

**Figure 3.** T1-weighted sagittal images obtained at 300/16 (TR msec/TE msec) with a matrix of 256 × 128 and half Fourier acquisition show magic angle effect involving the patellar tendon in a patient without symptoms referable to this region. **(a)** Increased signal intensity is observed within the apparently "buckled" patellar tendon (arrows). **(b)** Same image shows region of increased signal intensity occurring at 55° in relation to $B_0$, consistent with the magic angle effect (curved arrow).

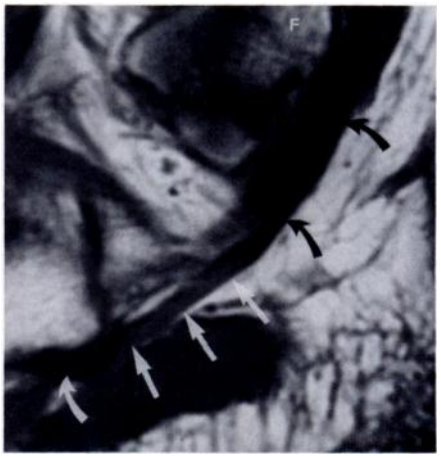



**Figure 4.** Sagittal T1-weighted image (500/13) obtained through the peroneus tendons by using a 256 × 192 matrix, two acquisitions, and 3-mm section thickness. Notice the prominent magic angle effect occurring within the peroneus longus tendon (straight arrows). The tendon both proximal and distal to this segment appears normally hypointense because orientation is not at, or near, the magic angle (curved arrows). *F* = fibula.

"banding" at microscopy. Berendsen initially showed dependence of T2 relaxation times on the orientation of relatively dehydrated tendons in respect to a static field (8). Fullerton et al and Peto et al (9,10) then observed similar findings in fully hydrated tendons obtained from recently killed animals. These workers revealed a marked influence on the T2 relaxation time with negligible effect on the T1 relaxation time. Augmentation of T2 relaxation times on the order of 100 times was demonstrated at the magic angle (9). These results were obtained at low field strengths, however, and it was thought that significant increased signal intensity would seldom be appreciated during routine clinical imaging (9).

Subsequent work at 1.5 T showed that tendon orientation significantly affects signal intensity during routine clinical short TE sequences (T1-weighted, spin-density, and gradient-recalled echo sequences) (11). Augmented T2 times attributable to magic angle effects approximated the TEs used in these sequences, resulting in moderately high signal intensity instead of the commonly expected marked hypointensity usually observed in tendons. Tendons or tendon segments that course at or near 55° in relation to $B_0$ are most commonly affected (Fig 3). The tendons of the ankle (Fig 4), extensor and flexor pollicis tendons of the wrist, and the long bicipital tendon of the shoulder are just a few common examples (11,12).

There is considerable debate over the cause of increased signal intensity in the rotator cuffs on short TE images obtained in asymptomatic volunteers. Since the inception of MR imaging of the shoulder, workers have attributed these regions to tendinitis, tendinosis, or frank cuff tears (13,14). Kjellin et al have shown histologic evidence of degeneration in cadavers, which may in part explain these foci (15). More recently, magic angle effects have been shown to have a role in the production of these relatively hyperintense regions (16) (Timins ME, Erickson SJ, Cox IM, unpublished data, 1993). We believe, therefore, that one should exercise caution when diagnosing cuff tears on the basis of signal intensity criteria at short TE imaging alone. A simple approach, which we use at our institution, is to evaluate T2-weighted images alone for evaluation of the cuff. Pathologic conditions are diagnosed on the basis of cuff irregularity or interruption, as well as on the presence of signal intensity alterations. Magic angle effects are much less apparent on T2-weighted sequences, because even significantly augmented T2 relaxation times are significantly less than the TEs used in these sequences. Such long TEs allow for dramatic T2 decay.

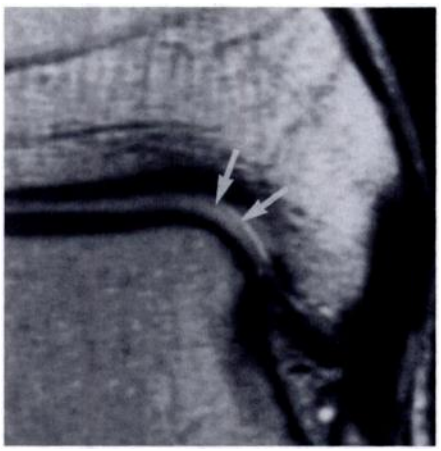
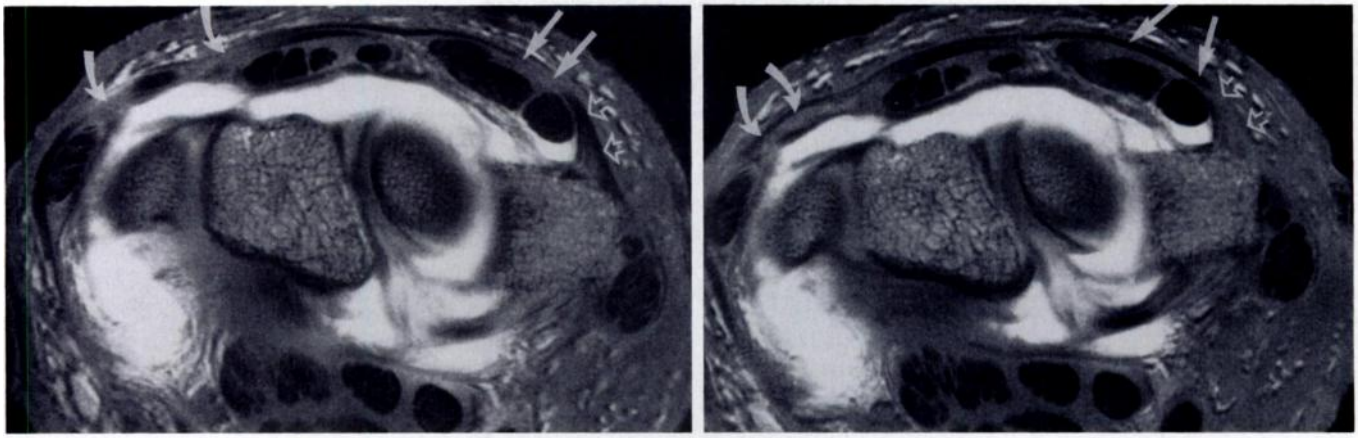


**Figure 5.** Coronal fast spin-echo, spin-density image (3,000/25) obtained through the medial talar dome by using a 256 × 256 matrix, four echo train length, two acquisitions, and 3-mm section thickness. The cartilage of the medial talus contains segments varying from 0° to 90° in relation to $B_0$. Possible increase in signal intensity is seen at or near the magic angle (arrows).

### Hyaline Cartilage

Rubenstein et al, in this issue of *Radiology*, elegantly present evidence of magic angle effects occurring in bovine hyaline cartilage (17). Hyaline cartilage, unlike tendon, contains only approximately 50% collagen by weight. It is composed of type II collagen, which shows a less regular structure and does not consistently aggregate to form fibers. Furthermore, the ultrastructure of cartilage is not uniform, but rather demonstrates multiple layers having predominant patterns of collagen orientation. These workers correlated cartilage layers observed with light and electron microscopy with laminae noted on MR images. Signal intensity in cartilage specimens was plotted against depth from the articular surface at different rotations of the specimen in relation to $B_0$. These quantitative data showed magic angle effects to be most prominent in lamina two. Visual inspection of the MR images of the hyaline cartilage specimens showed strikingly augmented signal intensity in those segments oriented 55° in relation to $B_0$.

Although in vivo cases of "simulated pathology" were not included in their



a. b.

**Figure 6.** T1-weighted (500/25) images obtained by using a 512 × 512 matrix, two acquisitions, and 3-mm section thickness show magic angle effect involving the extensor retinaculum. **(a)** Apparent discontinuity of the flexor retinaculum overlies the second extensor compartment (solid straight arrows). The retinaculum appears relatively hypointense near the osseous insertion site (open straight arrows). Other regions of apparent discontinuity are evident on the ulnar aspect (curved arrows). **(b)** This image was obtained by orienting the cadaver section 90° in relation to the position in **a** and then electronically rotating it to the corresponding position. Signal intensity is markedly increased near the osseous insertion of the extensor retinaculum (open straight arrows), with normally hypointense retinaculum in the region of the second extensor compartment (solid straight arrows) and intermediate signal intensity along the ulnar aspect of the wrist (curved arrows).

study, one can see how chondral disease may be misdiagnosed. Curved articular surfaces such as the femoral trochlear cartilage as viewed in the sagittal plane or the talar dome cartilage as seen in the coronal plane could prove interesting models (Fig 5). Now that the effect of orientation on hyaline cartilage signal intensity has been proved, other examples will undoubtedly be forthcoming.

### Other Tissues

The occurrence of magic angle effects in other collagen-containing tissues has not yet been described in the literature. We have, however, recently observed a striking example involving the extensor retinaculum of the wrist during a cadaver–MR imaging anatomic correlative study (Fig 6). Are ligaments, which are also composed of type I collagen, prone to magic angle effects? Presumably, the answer is "yes," with verification requiring only a simple experiment. It is possible that similar effects may be observed in other noncollagenous tissues during routine clinical imaging; subtle alteration of relaxation times in skeletal muscle, for example, has been shown experimentally (18). ■

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