Magnetic resonance imaging of short T2 relaxation components in the musculoskeletal system

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Introduction

One of the unusual features of magnetic resonance (MR) imaging of the musculoskeletal system is the fact that many of the tissues of most interest such as tendons, ligaments, menisci, periosteum, and cortical bone have short T2s and produce no signal when imaged with conventional pulse sequences. They have been described as MR “invisible.”

The lack of signal from the invisible tissues provides a useful dark background against which abnormalities that have an increase in signal can be recognized, but it also creates problems because the absence of signal means that it is not possible to characterize these tissues by measuring their mobile proton densities, T1s or T2s, actively manipulate their image contrast, differentiate adjacent tissues with short T2s, visualize short T2 internal structures within them, or observe effects due to contrast enhancement. These problems have meant that from a technical point of view, study of the MR-invisible tissues has lagged far behind that of visible tissues.

The T2 which represents the cut-off between visible and invisible tissues was about 10 ms using spin echo sequences on older MR systems [1] but with conventional gradient echo sequences and modern clinical machines, the cut-off has become shorter and is probably 1–2 ms for images with clinically useful spatial resolution.

Of particular interest have been ultrashort echo time (UTE) pulse sequences with TEs as short as 8 μ s. These were originally described in the 1990s [2, 3] but improved machine performance has led to images using these sequences with signal detectable from previously MR-invisible tissues at spatial resolutions comparable to those obtainable with conventional sequences in clinically acceptable scan times.

Tissue properties

Within the invisible group of tissues, (1) tendons, ligaments and menisci have T2s in the range of about 2–8 ms and (2) cortical bone, dentine, and the deep layers of articular cartilage have T2s of about 0.2–2 ms. This reflects the fact that solid or semi-solid tissues generally have shorter T2s than soft tissues or liquids. There is a third group of tissue components including membranes, crystalline structure and protons in proteins with T2s of 10 μ s or less. As will become apparent later, tissues in the first group can often be visualized with short TE gradient echo sequences, the second group requires ultrashort TE sequences or solid state sequences, and the third group of tissue components requires solid state sequences.

Besides the differences in T2, it is important to note that many tissues in the musculoskeletal system contain highly ordered collagen and that the T2 values of these tissues may increase markedly with orientation of the collagen fibers to B_0 towards the magic angle. In addition to this effect, there is a change in tissue susceptibility with orientation to B_0 for tendons and ligaments of about 3 ppm with fibers parallel to B_0 at the water end of the proton spectrum and fibers at 90° to B_0 at the fat end [4].

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Basic physics

In dealing with the visible tissues with T2s of 10 ms or greater, application of 90° or 180° radiofrequency pulses usually results in rotation of the longitudinal magnetization through the expected angle, but when the tissue T2 is short, and comparable with the pulse duration (e.g., 0.2–0.5 ms for 90° pulses and 0.5–25 ms for inversion pulses) transverse relaxation competes with excitation and the magnetization may be rotated though much less than the expected angle. This effect can be exploited, for example, with long 90° radiofrequency pulses to selectively excite long T2 relaxation components, while leaving short T2 components largely unaffected.

In addition, the application of an off-resonance pulse as used with magnetization transfer techniques may directly saturate short T2 components (which have a broad spectrum) and leave short T2 components which have a narrow spectrum unaffected. This leads to a direct reduction in signal in short T2 components in addition to the well-known indirect effect through reduction of magnetization transfer from the short T2 components to the long T2 components of the free pool. The reduction in the short T2 components may be detectable with appropriate sequences.

Fat saturation pulses may also selectively saturate short T2 water components and this effect may vary both with the T2 of the water components and the orientation of tissue collagen fibers to B₀, with fibers perpendicular to B₀ having resonance frequencies closer to the fat peak and, therefore, potentially more affected by fat saturation/pulses.

Solid-state imaging techniques using spectrometers

Imaging techniques using spectrometers have been used to study samples of materials and tissue in small bore spectrometers for many years. The most common method for imaging short T2 materials is single-point imaging where very short phase encoded pulses are used in three dimensions [5]. These allow the use of a single very short TE since only a single point is acquired (rather than a line of k-space with a range of TEs for the different points). The principle disadvantage of this technique is that the phase encoding in three directions means that the long acquisition times are required for reasonable degrees of spatial resolution. These techniques have been used in conjunction with various methods of suppressing fat and long T2 components. There are also hybrid variants where several points are acquired in order to reduce the imaging time [6].

Another method is to use continuous wave excitation, sweep through a range of frequencies and detect the absorption that occurs on resonance while a static gradient is applied across the sample [7].

A third method is SWIFT (Swept Imaging with Fourier Transformation) where the rf pulse is divided into component pulses with a short data acquisition after each pulse. This technique can be used in three dimensions in reasonable scan times [8, 9].

Small-bore spectrometers used for the study of materials and tissue samples usually have higher static fields, greater gradient performance, shorter rf pulses (e.g., 1–2 μs) and faster switching times between transmit and receive modes than clinical systems. The lower radiofrequency and gradient performance of clinical systems, and the time limitations for patient studies means that the range of techniques that can be used on them is much more limited.

Techniques used on clinical systems

Gradient echo approaches have been the initial method for imaging short T2 components and these offer the potential to detect signal in the higher range of the short T2 tissues such as menisci, ligaments and to a lesser extent, tendons. Although TEs of as short as 0.5 ms are possible, gradient limitations mean that these can only be achieved at relatively low spatial resolutions.

Ultrashort TE (UTE) sequences use short TEs (down to 8 μs) and radial acquisition with sampling during the ramp-up of the gradient allows detection of signals from short T2 tissues. With the two-dimensional form, slice selection is performed without a rephasing gradient and needs to be done in two stages.

Coupled with the detection of signal from short T2 components is the frequent need to suppress signal from long T2 relaxation components. This can be achieved with a long 90° pulse to selectively excite long T2 components and dephase them, a long 180° pulse to selectively invert long T2 components and null them, and subtraction of a later echo image from the first image. It is also possible to subtract an image taken with off-resonance saturation from one obtained with one without saturation to obtain an image whose content is very largely due to short T2 components.

It has also been possible to use the technique with spectroscopic imaging to obtain both spectra of short T2 components and images of tissue components present at various frequencies off-resonance [10].

As yet, single-point imaging methods and SWIFT have only been used to a very limited degree on patients. Almost all reported clinical studies have been with gradient echo or UTE techniques.

Cortical bone and periosteum

Signal from cortical bone is detectable with UTE sequences. Previously, normal bone could only be studied indirectly through imaging of bone marrow and other adjacent tissues. Periosteum which has a longer T2 than cortical bone can be differentiated and evidence of perfusion can be seen in both tissues using intravenous Gadolinium-DTPA [11]. The T1 of cortical bone is quite short and typically less than that of fat [12]. Cortical bone mobile proton density increases with age and is increased again in renal osteodystrophy [13]. Callus formation with periosteal continuity has been observed in fractures.

Tendons, ligaments, and entheses

These tissues produce detectable signal. Endotenon or endoligament can be differentiated from tensile fibrous tissues with the latter tissue usually showing shorter T2s. At entheses which are the junctional regions seen where tendon, ligaments or capsules are attached to bone, both uncalcified and calcified fibrocartilage are frequently present. In addition, in regions where tendons or ligaments are subject to compression, sesamoid fibrocartilage is often found within tendons or ligaments. Fibrocartilage is much more resistant to compression and shear force than tensile tendon, and usually has a longer T2. Entheses are frequently implicated in the overuse syndromes and are the principal site of involvement in the seronegative arthropathies. The capacity to image the structure of normal entheses with UTE sequences has provided the opportunity to observe loss of normal features early in disease, as well as relatively small changes in T2, rather than just the features seen late in disease after the tissue T2 has increased sufficiently so that abnormalities become detectable with conventional sequences [14, 15].

The meniscus of the knee

The detectable signal from the meniscus now means that it is possible to separately visualize the red and white zones using contrast enhancement [16]. This may be important in planning surgical approaches to repair of tears since those in the red zone show much greater capacity for healing than those in the white zone.

It is also possible to demonstrate at least five different fiber groups within the meniscus using GE and UTE sequences as well as magic-angle imaging. These include circumferential, radial, lamella, network, and vertical fibers. Within the meniscus, it is possible to differentiate more

central, mainly cartilaginous tissue from more peripheral mainly fibrous tissue. The organization of the fibers and the mechanical properties of the different types of tissue in the meniscus provide a basis for understanding the pattern of tears seen in clinical practice.

Articular cartilage

Articular cartilage has a range of T2 values from 30–40 ms for the more superficial layers decreasing to about 1–2 ms for the deepest calcified layer. The deep radial and calcified layers are not usually differentiated from subchondral bone with conventional pulse sequences. By using UTE sequences, these layers can be differentiated from subchondral bone with cartilage having a higher signal as a result of its higher mobile proton density [17, 18].

Peripheral nerve, muscle, and aponeuroses

Peripheral nerve contains collagen in the epi-, peri-, and endoneurium. This has a short T2 and shows a magic angle effect [19]. The pattern differs from tendons and ligaments where most of the magic angle effect is seen in region of the fibers with relatively little effect in the endotenon or endoligament. Muscle has a significant proportion of short T2 components which are readily seen using long T2 suppression techniques. Aponeuroses and fascia can be readily identified. Aponeuroses can be separated from tendon by their anatomic features.

The spine and red bone marrow

Ligaments of the spine and the cartilaginous end plates of intervertebral discs show detectable signal with UTE sequences. Red bone marrow includes short T2 components in the hematogenous tissue which contains iron and has a short T1 as well as short T2. This may provide a useful basis for recognizing conditions which have longer T1s and T2s in the short T2 range. Iron accumulation can be recognized in disks in thalassemia [20].

Calcification

Calcified tissue shows a variety of patterns. When T2 is prolonged, calcification may be detectable even with conventional sequences and appear high signal because of its relatively short T1. In other cases, calcification may be dense and appear low signal even with UTE sequences.

These differences may reflect degrees of dehydration, other chemical factors, the chronicity of disease and the context in which calcification occurs.

Contrast agents

The detectability of signal with UTE sequences means that contrast enhancement may be seen in tissues such as tendons, ligaments, and cortical bone where changes have not previously been accessible. The detectable signal also means that there is a role in the tissues for contrast agents such as magnetic iron oxide particles which reduce signal. These effects of this type of agent are not apparent when the tissue signal is zero as it is with conventional sequences. The use of subtraction can make the effect of shortening T1 and T2 additive in terms of tissue contrast.

Artifacts

There are a variety of artifacts with UTE sequences. Two of particular interest are chemical shift, which with radial imaging takes the form of displacement of boundaries generally (rather than just in the frequency direction as with clinical imaging), with an adjacent absence of signal. This increases with field strength and the use of lower-receiver bandwidths [21].

Another artifact is T2 blurring due to decrease of the MR signal during acquisition [22]. This results in indistinct margins but also represents a trade off between signal-to-noise ratio (SNR) and acquisition time, and with acquisition times up to six T2s it can be minimized providing that the SNR is adequate [23]. The concurrent imaging of longer T2 tissues may also mean that boundaries between two tissues are well maintained. In addition, display considerations at high contrast boundaries may reduce apparent blurring.

Contrast mechanisms

At first, site use of a short TE to detect signal from tissues irrespective of their T2s could be expected to lead to relative bland T1-weighted or mobile-proton-density-weighted images with low intrinsic contrast.

In fact, there are several very effective contrast mechanisms in the short T2 range which can produce high contrast between different short T2 tissues. These include the use of subtraction to emphasize short T2 components on images, the use of long inversion pulses to produce T2 contrast by selectively inverting longer T2 components, and the use of off-resonance pulses (including fat saturation) to

selectively decrease the signal from shorter T2 components and so, produce T2 contrast in the short T2 range.

Boundaries

The imaging of tissue and fluid boundaries raises several issues. Firstly, these may not have previously been observed with conventional imaging with tissues that have short T2s. There are also often different anatomic configuration of tissues at boundaries such as the deep layers of cartilage, periosteum, entheses, and other tissue modifications. Many of these tissues have different susceptibilities and this may create effects at boundaries which are minimal with UTE sequences but may not be so with subtraction images. There are also chemical shift artifacts of different types. Partial volume effects may be prominent in structures at boundaries. The fascicular structure of tissues may be lost depending on the fiber to slice orientation. Magic angle effects may also produce marked changes in contrast which change the appearance of boundaries. Directional susceptibility effects can also change boundary appearances especially when coupled with off-resonance saturation.

Conclusion

The previously invisible short T2 tissues are an area of particular interest in musculoskeletal radiology and techniques are now being developed to access these tissues with images having spatial resolution comparable to that used in routine clinical imaging.

Newer approaches such as SWIFT and faster forms of single-point imaging are likely to enter the clinical domain and extend the range of study of short T2 components. Studies of perfusion and diffusion in previously invisible tissues are just some of the new possibilities now available as a consequence of these developments.

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