[Guest Editorial]

Updates in Musculoskeletal Imaging

Many musculoskeletal imaging advancements have been made within the past decade. Initial emphasis was placed on diagnosis, demonstrating that imaging can provide a noninvasive, accurate assessment of joint integrity, typically using arthroscopic surgery as a standard. More recent advances to improve both in-plane and through-plane resolution as well as tissue contrast now enable complete comprehensive assessment of the joint, providing detection of lesions that cannot be seen during arthroscopy, either because they are not accessible or because they are present within the deeper structures of the cartilage-bone interface. Magnetic resonance imaging (MRI) has evolved from a tool that demonstrates anatomy to one that noninvasively assesses tissue biochemistry by the use of parametric mapping techniques, including T2 mapping, T2* mapping, and T1 rho. These quantitative MRI (qMRI) techniques provide a more sensitive means to detecting tissue pathology before structural breakdown is apparent on high-resolution morphologic images, allowing for risk assessments in cohorts with predispositions toward musculoskeletal pathologies such as the early onset of osteoarthritis (OA) in patients with developmental hip dysplasia, femoroacetabular impingement (FAI), or after anterior cruciate ligament (ACL) injury in the knee. These techniques also provide a noninvasive assessment of cartilage repair surgeries, obviating the need for second-look arthroscopy. More recent advances have been to link parametric mapping techniques to structural capacity of tissue to bear load. Combined, these data can benefit the clinical management of musculoskeletal injuries, as they provide a quantitative metric by which to guide treatment plans, evaluate intervention efficacy, and better inform decisions regarding the appropriate timing for return to play. While many advances have been made in imaging, this current report will focus on 3 of the more recent advances, including an update on MRI parametric mapping, peripheral nerve imaging, and shear wave sonoelastography.

ULTRASOUND ELASTOGRAPHY

Ultrasound elastography can detect changes in tissue stiffness, and shear wave elastography (SWE) has the ability to provide a quantitative assessment of such changes. Studies evaluating SWE in musculoskeletal soft tissue structures (ie, muscles and tendons) have shown sufficient repeatability[56,58,67,80] and provide technical guidelines on measuring musculoskeletal tissue stiffness.[39,78,90]

Although its musculoskeletal applications are only just emerging, there are some promising developments on the utility of SWE in sports medicine. Several studies have correlated SWE measurements in muscle and tendon to biomechanical tissue properties.[49,69] There are numerous studies characterizing tendinopathy with SWE (Figure 1).[5,15,19] Others have correlated symptom scores for tendinopathy to SWE measures, with some showing better correlation with SWE than conventional ultrasound techniques.[23] SWE has also demonstrated the ability to detect changes in intrinsic tendon stiffness in asymptomatic athletes compared with age-matched healthy nonathletes.[6] These and other studies have established the potential for SWE to inform on musculoskeletal tissue health beyond the capabilities of conventional ultrasound.

qMRI AND PARAMETRIC MAPPING TECHNIQUES

Over the past decade, qMRI techniques have been developed as a noninvasive means by which to evaluate the biochemical status of tissues. These techniques work by exploiting inherent differences in MRI tissue relaxometry that reflect tissue integrity. Currently, the most commonly used qMRI sequences can largely be divided into 2 general categories: proteoglycan (PG)- or glycosaminoglycan (GAG)-sensitive techniques and collagen-sensitive techniques (Table 1).

Proteoglycan-Sensitive Techniques: T1ρ and T1 (dGEMRIC)

T1ρ Mapping

Quantification of T1ρ allows for mapping of the low-magnitude movements and interactions between constrained water protons and their local environment. Accordingly, quantitative measurements of T1ρ reflect the loss or gain of matrix constituents that work to retain water, such as the negatively charged GAG side chains on PG macromolecules, which impart resistance to compressive loads in articular cartilage. T1ρ values have demonstrated strong correlations with both histological PG content and fixed charge density in cartilage,[2,84] with an

DOI: 10.1177/1941738118780230

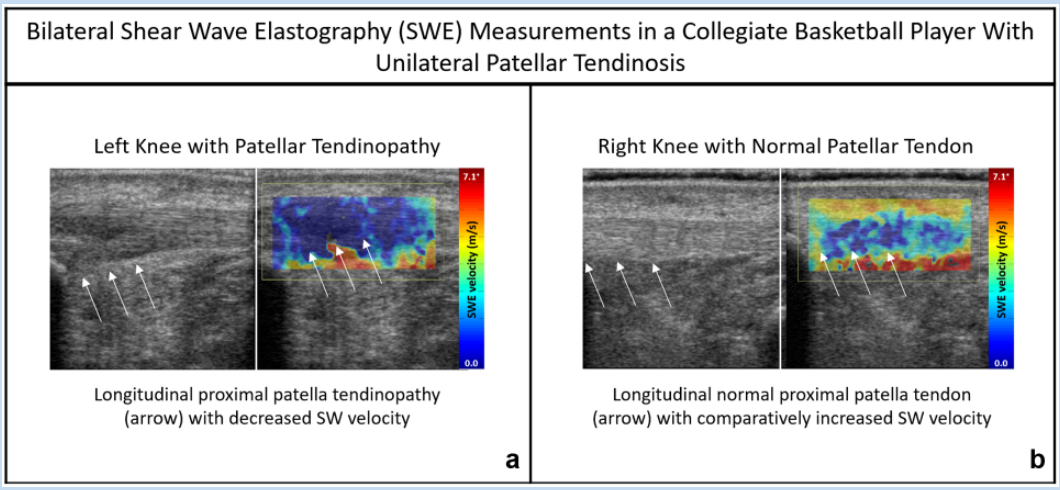

Figure 1. (a) Left knee displays patellar tendinosis and comparatively lower (deep blue) SW velocity in comparison to the contralateral (right) knee. (b) Increased (lighter blue) patellar tendon SWE velocity (m/s) demonstrated within the normal, healthy right knee of the same subject.

Table 1. Clinically useful qMRI techniques for assessment of the biochemical composition of tissues

MRI Technique	Biostructural Property Evaluated	Strengths	Limitations
T1ρ mapping	PG/GAG content and distribution	Sensitive to early PG depletion; does not necessitate use of contrast agent	Optimal at 3T; not available at all institutions
dGEMRIC	PG/GAG content and distribution	Well validated as an indirect measurement of PG/GAG content (high sensitivity and specificity)	Requires use of Gd contrast agent (contraindicated in patients with renal impairments); long delay (≈1.5 hours) between Gd administration and postcontrast MRI
T2 mapping	Collagen orientation and water content	Well validated; does not necessitate use of contrast agent; compatible with most MRI systems and field strengths	Susceptible to magic angle effects; cannot evaluate deeper (calcified) cartilage layers or other short T2 species (tendon, bone, ligaments, etc)
T2* mapping	Collagen orientation and water content	Does not necessitate use of contrast agent; can be faster than T2 mapping; UTE sequences allow for evaluation of short T2 species (calcified cartilage layer, tendon, ligament, etc)	Susceptible to magnetic field inhomogeneities and magic angle effects

dGEMRIC, delayed gadolinium-enhanced magnetic resonance imaging of cartilage; GAG, glycosaminoglycan; Gd, gadolinium; MRI, magnetic resonance imaging; PG, proteoglycan; qMRI, quantitative magnetic resonance imaging; UTE, ultrashort echo time.

elevation of T1ρ values indicative of a net loss of PG.[20,36,61] Previous reports have found that T1ρ values are capable of differentiating OA patients from healthy controls,[76] and strong correlations have been demonstrated between T1ρ values and in vivo measurements of disease severity within OA patients.[44] T1ρ measurements of cartilage have also proven to be well

correlated to arthroscopic findings in patients with posttraumatic cartilage injury and chondromalacia.[48,89]

T1 Mapping (dGEMRIC)

Alone, T1 relaxometry is not adequately sensitive to provide meaningful information about the biochemical composition of articular or meniscal cartilage. However, quantification of T1 relaxation can be useful in the presence of a negatively charged gadolinium (Gd) contrast agent, which is repelled by the negative charges of GAG and therefore diffuses toward areas of low GAG concentration. In this way, delayed gadolinium-enhanced magnetic resonance imaging of cartilage (dGEMRIC) allows for evaluation of the fixed charge density content and distribution of PG and associated GAG. Decreased dGEMRIC indices have been found in osteoarthritic cartilage as well as in the cartilage of patients with other joint conditions such as FAI, ACL injuries, and meniscal injuries.[26,27,40,51,59,81,86] In addition, several studies have provided evidence that dGEMRIC indices afford clinically useful predictive information about progression of joint degeneration and outcomes of surgical intervention.[10,21,52,65] Drawbacks of dGEMRIC techniques are both the required delay (approximately 90 minutes) between the administration of the Gd contrast agent and postcontrast MRI acquisition and the fact that Gd is contraindicated in patients with impaired renal function, limiting its more ubiquitous application.[28]

Collagen-Sensitive Techniques: T2 and T2*

T2 Mapping

T2 characteristics of a tissue reflect the interaction between free water protons (spins) within the tissue and how rapidly they diphase relative to one another after the application of a radio frequency pulse. Anisotropic and compact tissue structures force more interactions between the proton spins resulting in more rapid dephasing, which will manifest as a shorter T2 decay. In this way, T2 relaxation times are sensitive to both tissue hydration and orientation of collagen within a tissue matrix and can be comprehensively evaluated either on a voxel-by-voxel basis (voxel-based relaxometry) or through the analysis of T2 maps (texture). Injuries or degenerative processes that result in damage to a tissue's matrix will manifest as a prolongation of T2 relaxation times, as spin-spin interactions within the tissue will be decreased.[3,25,46,47,54,60,75,85] Recent studies have used T2 relaxometry as an image-based biomarker for the detection of early changes associated with cartilage degeneration as well as a quantitative metric by which to monitor disease progression and intervention efficacy.[7,8,11,25,32,33,38,42,45,53,57,60,61,64,65,68,70,71,77,79,87] Within knee OA patients, mean T2 values have been shown to be significantly correlated with pain, function, and morphologic cartilage measurements.[25] Notably, cartilage T2 measurements in patients without evidence of severe OA at baseline have also been found to be predictive of morphologic progression of OA at 2-year follow-up.[35,61,79] Similarly, a recent prospective study by Williams et al[87] demonstrated that early changes in articular cartilage T2 metrics after ACL injury correlated with later changes in both cartilage T2 and cartilage thickness. Prolonged cartilage T2 values have also been found in the talocrural and subtalar joints within patients who suffer from chronic lateral ankle instability.[35,79] In a recent study of patients with FAI, Samaan et al[70] reported that voxel-based relaxometry analysis of T2 radial heterogeneity was better able to detect cartilage delamination compared with global T2 mapping and that FAI patients with more severe cam impingements displayed increased T2 heterogeneity.

T2* Mapping

While T2 mapping is useful for the evaluation of cartilage, standard techniques are insensitive to short and ultra-short signal decays and are therefore limited in their ability to evaluate the deeper cartilage layers. Standard T2 mapping techniques are similarly inappropriate for the assessment of other short T2 species such as tendons, ligaments, and bone, as a majority of the signal will have decayed prior to echo formation. Therefore, specialized ultrashort echo time MRI techniques have been developed to effectively capture these rapidly decaying signals and allow for quantitative evaluation of T2*.[13,14,18,24,43,55,63,66,82,85,88]

Previous studies have established good correlations between T2* values, histopathology, microscopy, and biomechanical testing.[38,50,72] As with T2 metrics, numerous studies have demonstrated that prolonged T2* values are indicative of the presence and severity of tissue pathology.[12,34,38,50,85] Evaluation of meniscal samples obtained from patients undergoing total knee arthroplasty has established that regions with significantly prolonged T2* values also display corresponding histological degeneration.[50] In a recent study, Titchenal et al[82] reported that patients 2 years post–ACL reconstruction demonstrated elevated T2* values within the deep layers of the medial tibiofemoral cartilage compared with uninjured controls. Interestingly, the same study also reported that elevated T2* values correlated with higher knee adduction moment and a more varus mechanical axis, both of which have been previously implicated as factors contributing to risk of OA development.[82] As degenerative changes often precede tendon rupture, evaluation of T2* values has also proven useful for the evaluation of tendinosis.[14,34,63] Future applications of these techniques will be directed to correlating MRI assessment of collagen orientation to material properties, such as the patellar tendon in elite basketball players,[4] as T2* values are also affected by direct tissue loads.[37] Such quantitative assessments, like shear wave sonoelastography, may provide an objective noninvasive assessment of the ability of tissues such as tendons and ligaments to withstand repetitive loads, which has implications with regard to athletic performance and return to play.

PERIPHERAL NERVE IMAGING

Peripheral nerve diagnostic imaging has rapidly evolved over the past 20 years with advances in both ultrasound and MRI. In 1992, Howe et al[30] coined the term *MR neurography* to describe

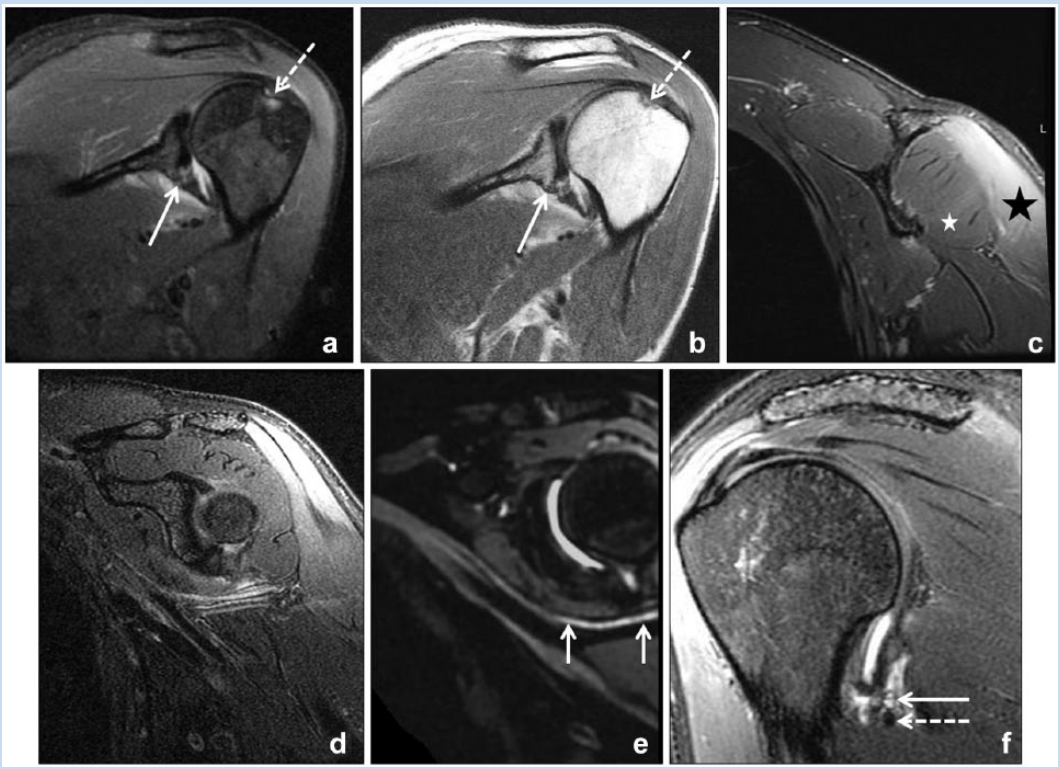

Figure 2. A 33-year-old woman status post left shoulder dislocation. (a) Oblique coronal inversion recovery and (b) proton density magnetic resonance images of the left shoulder demonstrate a Hill-Sachs lesion (dashed arrow) and partial capsular detachment from the scapula (solid arrow). Dedicated magnetic resonance imaging of the left axillary nerve was acquired at 6-week follow-up to evaluate a dense axillary nerve palsy postdislocation. (c) Coronal T2-weighted Dixon fat-suppressed image confirms denervation edema of deltoid muscle (black star) and relative sparing of the teres minor (white star). (e) Axillary nerve (arrows) is better delineated from adjacent vessels on vascular-suppressed, 3-dimensional T2-weighted curved multiplanar reformatted image compared with (d) the 2-dimensional image without vascular suppression. (f) T2-weighted sagittal image confirms suspected stretch injury, with signal hyperintensity of the axillary nerve (solid arrow) adjacent to the capsule with the posterior circumflex humeral artery (dashed arrow).

MRI sequences that combined fat suppression and diffusion techniques to optimize contrast in order to distinguish peripheral nerves from adjacent soft tissue. Only within the past 10 years, with the advent and availability of high-performance gradient 3.0-T magnets and multichannel surface coils that facilitate high–spatial resolution acquisition, has MRI become routinely effective in evaluating peripheral nerve pathology (Figure 2).[16] Nonetheless, MR neurography is not ubiquitous in radiology practices today, as it requires careful planning and real-time monitoring by specialty-trained radiologists and experienced technologists to ensure success.

MRI complements electrodiagnostic testing (EDX) for the evaluation of peripheral neuropathies and is comparatively noninvasive, painless, potentially less prone to interobserver reliability, and can often accurately localize the site of focal pathology.[29,41] Precise localization can potentially save hours in the operating room and decrease patient morbidity associated with extensive nerve exploration. MRI also affords concomitant assessment of all regional muscles within a prescribed field of view when evaluating for denervation, whereas EDX involves direct needle electromyography of each individual muscle. One potential pitfall of EDX localization is when a "lesion" does not involve the entirety of a nerve but rather comprises partial insult to 1 or more of its fascicles. EDX may then erroneously pinpoint pathology within a more distal branch nerve rather than within the parent nerve. A prime example of this is anterior interosseous neuropathy, a subtype of Parsonage-Turner syndrome. In this scenario, recent MRI studies (with surgical confirmation) have demonstrated an idiopathic hourglass constriction of the anterior interosseous fascicular bundle of the median nerve proper, immediately proximal to the elbow joint.[73,74] This finding directs surgical management in cases of refractory disease to neurolysis at the fascicular level rather than "decompression" of the anterior interosseous nerve proper within the forearm, as has been traditionally performed based on EDX localization.

Peripheral neuropathies commonly encountered by sports medicine specialists and routinely diagnosed with MR neurography include ulnar neuropathy in the throwing athlete, axillary neuropathy after shoulder dislocation, sciatic neuropathy following hamstring tear, and common peroneal neuropathy following knee dislocation. Even more common is iatrogenic injury following orthopaedic surgery (eg, direct impingement by orthopaedic hardware, stretch injury, compression from hematoma/seroma, and nerve transection). In these settings, MRI can pinpoint specific pathology and facilitate early intervention, or alternatively provide reassurance to both the surgeon and patient that no injury has occurred. Metal artifact reduction techniques, similar to those used for arthroplasty imaging, can be combined with MR neurography techniques to determine the precise relationship of hardware to the nerve in question.[1,62] Ultrasound also nicely complements MR for the evaluation of nerves, particularly when metal artifact reduction techniques are overwhelmed by a susceptibility effect from the metal.

In addition to hardware advancements, the development of novel pulse sequences has also assisted the evolution of MR neurography. Heavily T2-weighted fat-suppressed sequences, critical for elucidating nerve pathology, have improved with the advent of Dixon fat-water suppression techniques that provide robust fat suppression in regions notoriously difficult to achieve adequate suppression and a high signal-to-noise ratio. These can be combined with 3-dimensional acquisitions and reconstructed into multiple arbitrary planes to follow the course of a nerve.[17] Specialized vascular-suppression techniques have facilitated more reliable nerve identification and confidence in interpretation as they enable suppression of signal within the blood vessels that run alongside or in close proximity to the nerve of interest.[9,73,83]

One major limitation of MR neurography is its overall qualitative nature and inability to reliably quantify the extent of nerve injury and regeneration, particularly when a nerve remains in continuity (eg, stretch or compression injury). Diffusion tensor imaging, a qMRI technique developed for the brain that measures the degree of anisotropy, or preferential movement of water molecules in a particular direction, has been used for the assessment of peripheral nerve structural integrity.[31] As healthy nerves are inherently anisotropic given their longitudinal organization, damage to a nerve is typically reflected as decreased anisotropy. Peripheral nerve diffusion tensor imaging, however, is still a research tool with numerous technical hurdles that will need to be addressed before becoming a mainstay in clinical practice.

Peripheral neuropathies, as previously mentioned, are encountered in sports medicine practice often as a secondary insult after sports injury or surgery. As peripheral nerves, even small sensory branches,[22] can be visualized on routine MRI examinations (eg, of the knee or elbow), it is imperative that musculoskeletal radiologists familiarize themselves with the relevant anatomy and add these structures to their routine "search pattern." It is our experience in partnering closely with peripheral nerve surgeons, neurologists, and physiatrists over the past 5 years that MR neurography provides a valuable element in patient care.

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Each issue of *Sports Health* in 2018 will feature a Guest Editorial highlighting changes seen in both the journal and the disciplines of athletic training, orthopaedic surgery, primary care, and sports physical therapy, as well as this special update on imaging over the past 10 years. Be sure to look out for the continuation of this series in the September/October issue!