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Review

Role of chemical shift and Dixon based techniques in musculoskeletal MR imaging

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ABSTRACT

Fat suppression technique is a valuable resource in musculoskeletal magnetic resonance (MR) imaging that is helpful in the diagnosis and differentiation of various pathologies. Multiple different techniques are available for fat suppression, including frequency selective pulse sequence, inversion recovery, hybrid technique, chemical shift imaging (CSI) and the related Dixon based approach. The utility of CSI and Dixon approach is not well recognized in the domain of musculoskeletal MR imaging. The aim of this article is to review the various options for fat suppression and present focused discussion of the role of CSI and Dixon techniques for musculoskeletal MR imaging.

1. Introduction

A variety of fat suppression techniques are used in musculoskeletal magnetic resonance imaging for the diagnosis and differentiation of various pathologies. These include frequency selective pulse sequence, inversion recovery, hybrid technique, chemical shift imaging (CSI) and the related Dixon-based approach. The different techniques encompass various advantages and disadvantages, which make them suitable for different settings, protocols and magnet strengths, e.g. frequency selective fat suppression is best employed for small field of view with dedicated joint coil while inversion recovery provides best fat suppression at low field magnet strength or along curvatures of the extremities and off-center areas. Chemical shift imaging (CSI) with in-phase (IP) and opposed-phase (OP) imaging is an established and widely used technique for the detection and characterization of pathologies in the liver, renal, and adrenal lesions [1]. There has been a recent interest in use of CSI and Dixon-based approaches in the domain of musculoskeletal imaging for marrow and focal lesion imaging, however, there is paucity of literature in the discussion of role of these techniques in the enhancement of image contrast resolution, evaluation of inter-trabecular fractures, avascular necrosis, and defining fatty infiltration or blood products in various tissues. In this article, we will discuss technical considerations of different fat suppression techniques with emphasis on the role of CSI and Dixon approaches in the domain of musculoskeletal MR imaging.

2. Physics and technical considerations

Hydrogen nuclei of fat and water are the primary contributors to MR signal and their depiction depends on differences of two key properties: precessional frequency and rate of nuclear spin-lattice relaxation (T1) time. These properties are used to generate signals with reduced contribution from fat but continued contribution from water. Inversion recovery based and hybrid techniques capitalize on differences in T1 relaxation times. On the contrary, chemical shift based and frequency-selective based sequences exploit differences of precessional frequency between fat and water protons [2].

Frequency-selective fat suppression involves an excitation pulse with a narrow bandwidth centered on the Larmor frequency of fat that selectively tips the magnetization vector of fat to the transverse plane. A spoiler gradient is then applied to dephase protons and suppress the fat signal. Images are simultaneously acquired before recovery of longitudinal magnetization of fat begins. Fat saturation helps increase image contrast resolution and highlights lesions such as contrast-enhancing tissue, edema, and blood products by eliminating the confounding signal of fat. Off-center imaging, large field of view, metal implants and air-tissue interfaces are unsuitable for this type of imaging.

Inversion Recovery, i.e. short inversion time recovery (STIR) sequence capitalizes on relatively shorter T1 of fat than water to suppress fat signal [3]. The technique involves a non-selective 180° pulse that inverts the longitudinal magnetization of both fat and water. As the longitudinal magnetization recovers for each tissue, fat reaches the null magnetization line in a shorter period of time than water. A 90° excitation pulse is fired immediately after the inversion time to produce a

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fat-free signal [4]. STIR is insensitive to B0 heterogeneity and is suitable in imaging off-center, metal, different air-tissue interfaces (fingers, toes, brachial plexus), and large field of view (whole spine imaging). The inversion time varies from 150 to 160 ms on 1.5 T (tesla) scanner to 220–230 ms on 3T scanner. Disadvantages are relatively long imaging time and low signal to noise ratio (SNR). In addition, nonspecific and non-selective fat signal suppression can significantly lower the signal from other tissues or products with short T1 relaxation times, such as methemoglobin, gadolinium, muscle, proteinaceous tissue, and melanin. Therefore, STIR imaging is also not suitable following administration of a paramagnetic contrast agent to detect abnormal tissue enhancement. Recently, STIR has been used to obtain selective magnetic resonance imaging of brachial plexus following administration of intravenous gadolinium. [5].

Hybrid techniques such as, spectral-selective inversion recovery (*SPIR*) and spectral-selective adiabatic inversion recovery (*SPAIR*) suppress fat by a combination of frequency selective fat suppression and inversion recovery techniques [2]. While SPIR being more frequency selective is sensitive to B0 and B1 heterogeneity, the adiabatic pulse in SPAIR renders this sequence relatively less sensitive to B1 heterogeneity and provides an extremely uniform fat suppression. Furthermore, SPAIR permits greater SNR than STIR, is acquired in shorter time, and is more SAR (specific absorption rate) favorable. In authors' experience, it also results in less pulsation artifacts [6,7]. SPIR and SPAIR techniques are more susceptible to hardware artifacts as compared to STIR imaging (Table 3)

3. Chemical shift imaging

The protons of fat and water induce a different magnetic effect on the net magnetic field strength experienced by them due to different size and polarity in the molecules. This leads to a reduced precessional frequency of fat versus water protons. Chemical shift is the product of this resonant frequency difference divided by a reference resonant frequency, which increases proportionate to B0. On a 1.5-T scanner, chemical shift leads to a 225 Hz difference in precessional frequency of fat relative to water, while on a 3.0-T scanner this difference is 450 Hz. Furthermore, chemical shift is inversely related to the square root of receiver bandwidth. CSI exploits these differences in fat and water to produce in-phase (IP) and out-of-phase (OP) images. IP images are obtained with a time to echo at which fat and water protons exhibit phase coherence (4.4 msec at 1.5-T; 2.2 msec on a 3.0-T magnet). OP images are obtained with a time to echo at which fat and water protons are 180° out of phase (2.2 msec at 1.5-T; 1.1 or 3.3 msec on a 3.0-T magnet) [8]. Thus, OP images have the absolute value of intravoxel signal from water with the fat signal cancelled. Decreased signal intensity on the OP images relative to IP images advocates the presence of microscopic fat. Artifacts reliably occur at fat-water interfaces as a result of chemical shift artifact. OP images are quickly recognized due to this artifact, which has been termed the etching or India ink phenomenon (Fig. 1) [9].

4. Dixon based imaging

Pure water and pure fat images can be reconstructed by post-processing of data obtained in similar fashion to CSI [10]. The pure water images are formed by ***adding*** the IP and OP data sets, while pure fat images are formed by ***subtracting*** the OP image from the IP dataset. These images help differentiate fat and water content of various voxels in the image. This method, termed the two-point Dixon technique is insensitive to B1 heterogeneity and may be used in a variety of sequences and has been shown as a good technique for achieving uniform fat suppression in the distal parts of the extremities [11]. However, this method is limited by B0 heterogeneity, which leads to phase errors and undesired suppression of water and fat signals. Therefore, the three-point Dixon method was introduced, which adds a third set of images to compensate for B0 heterogeneity [12]. The third image set is obtained after a 180° phase shift such that fat and water protons are phase coherent [13]. Other developments of this method include the iterative decomposition of water and fat with echo asymmetry and least-squares estimation (IDEAL), a modification of the three-point technique which times acquisition of the three images at different phases between the water and fat signals [14]. These modified techniques are insensitive to B0 and B1 heterogeneities and produce more homogenous fat suppression even in areas of high susceptibility or where chemical fat saturation is difficult, such as the neck or lung apices. Other advantages include a high SNR, even in the areas with high magnetic susceptibility, such as metallic implants. Dixon technique can be added to T1-weighted [15], T2-weighted [16] and proton density (PD) weighted images [17]. Additionally, quantification of intra-voxel fat and iron fractions can be performed using T1-weighted Dixon quant imaging (Fig. 2) [18].

Disadvantages of the Dixon technique include the need for longer scan times, which can lead to increased risk for motion and breathing artifacts. These can be partially mitigated with a multi-transmit coil. Other pitfalls include water-fat swap artifact, which is the inappropriate suppression of water or fat due to a shift in water and fat peaks (Fig. 3). Newer versions of Dixon technique that employ calculations from multiple echoes and fat peaks promise to mitigate such artifacts. Suggested parameters for T2-weighted Dixon and CSI from authors experience using multiple vendor platforms have been illustrated in Table 1.

5. Role of CSI and dixon sequences in various musculoskeletal pathologies

The role of CSI and Dixon in musculoskeletal pathologies with expected signal alterations are illustrated in Table 2 and key points are discussed below.

5.1. High resolution Joint imagingHigh resolution joint imaging

While CSI produces IP and OP imaging, instead Dixon imaging provides pure fat and water maps. On current 1.5-T and 3-T scanners, in author's experience, one can replace the routinely used fat suppressed PD-weighted pulse sequence in at least one plane with T2-weighted or PD-weighted Dixon sequence. The combination of fat and water contrast images can therefore illustrate the various layers of the ligaments and retinaculae s without additional time penalty. These allow the reader to accurately measure the thickness of the ligament or

Table 1
Parameters for T2 Dixon and CSI used for musculoskeletal imaging at authors' institution.

	TR (ms)	TE (ms)	Matrix	Slice thickness (mm)	FOV (mm)	Gap (mm)	Flip angle	Bandwidth (kHz)
Siemens 1.5 T	4710	53	256 × 256	4	130	0.4	180	41
Phillips 3T	3087	55	256 × 221	4	110	0.4	90	72
GE 1.5T	3000	35	256 × 192	3	90	0.3	90	25
GE 3T	3000	55	320 × 256	3	150	0.3	90	125