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Fast triple-spin-echo Dixon (FTSED) sequence for water and fat imaging

Radim Korinek *, Karel Bartusek, Zenon Starcuk Jr

Institute of Scientific Instruments of the CAS, v. v. i., Czech Republic

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A B S T R A C T

A number of 'Dixon' techniques based on fast spin echo (FSE) sequence have been proposed and successfully used in many branches of medicine. Some require only one scan, but most of them need multiple scans and long scan times. This article describes a new fast triple-spin-echo Dixon (FTSED) technique suitable for ultra-high field MRI, in which three specific time shifts are introduced in the echo train; thus, three images with defined water-fat phase-differences (0, π, 2π) are encoded in the phase of the acquired images without extreme restrictions upon the echo duration. The water and fat images are then calculated by iterative least-squares estimation method. The sequence was successfully implemented at a 9.4 T ultra-high field MRI system and tested on a phantom and a rat.

1. Introduction

MRI provides excellent contrast between soft tissues by exploiting the properties of hydrogen atoms and their molecules, which are predominantly those of water but also, to some extent, of lipids. It is well known that fat stored in adipose tissue forms a significant part of the human body and can be used as a biomarker [1] in many branches of medicine. Fat can, however, also impede proper diagnostics or generation of quantitative images by its interference with signals from water. Therefore, fat suppression and water-fat separation techniques are widely used in MRI for enhancing image contrast, for avoiding artefacts due to spectral differences between the water and lipid signals, and for quantification of fat in adipose tissue. Suppression/separation of water and fat is very useful in the diagnostics of fatty liver disease (FLD), and it also finds applications in contrast-enhanced imaging, in cardiology, and other clinical examinations or branches of medicine. For instance, the amount of fat in the tissue can be applied as a biomarker in non-alcoholic fatty liver diseases (NAFLD) [2,3] or cardiac steatosis [4].

Nowadays fat separation or suppression is a common part of many MRI protocols. The first articles describing various approaches for the separation/suppression of water and fat appeared almost 30 years ago [5,6,7]. Methods for water and fat separation are based on two physical principles: longitudinal relaxation T_1 and/or chemical shift (CS). Water/fat separation or fat-suppression imaging methods can be classified into four main categories: inversion recovery (IR) [5,8,9]; Fat-Sat. [6]; spectral-spatial selective excitation [10,11,12]; and finally 'Dixon' methods based on the original Dixon method [7]. Besides application in humans, these techniques can be employed for similar preclinical purposes in small mammals.

Dixon water-fat separation methods are chemical shift-based water-fat separation methods. Their attractivity consists in several facts: unlike inversion recovery, they involve no magnetization preparation, which requires longer excitation, an inversion RF pulse, and relies on a sharp and known value of fat T_1 relaxation time; unlike chemical-shift based fat saturation, they are able to account for B0 inhomogeneity much lower than the chemical-shift difference between water and fat signals; and finally unlike spectral-spatial selective excitation, no special RF pulses and again superior shimming quality are required. Instead, they utilize the difference between water and fat spectra in principle in the same voxel, hence exposed to the same static field B_0. Due to the lower shielding in water molecules, water protons precess slightly faster than fat protons. The various ^{1}H protons in a lipid molecule are not shielded equally, however, so the spectrum of fat contains several spectral peaks of different intensities; the main fat peak is placed at a distance of 3.5 ppm from a single water peak, and it can be exploited/used to produce a controlled phase shift between the water and fat signals.

Dixon methods are very flexible and can be implemented into many imaging sequences, as the wide range of clinical applications indicates [13,14,15,16,17]. Dixon methods can be classified as single-point (SPD or 1PD) [18], two-point (2PD) [19,20,21,22,23,24,25], three-point (3PD) [26,27,28] and multipoint (MPD) [29,30,31,32,33]. The various implementations attempt to overcome several common problems of all Dixon methods. Firstly, magnetic field inhomogeneity owing to magnetic susceptibility and shimming imperfection, together with chemical

* Corresponding author.
E-mail address: radim.korinek@gmail.com (R. Korinek).

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shift displacement, affect the exact resonance frequencies; therefore, since the inception of these methods, research has been continually focused on finding the field inhomogeneity [34,26,19,22,33,35]. The second priority has been reducing the measurement time [36,37,38]. Thirdly, the false original assumption of a single fat resonance has been refined by accepting a fat proton spectrum having several spectral peaks [39,40]. The inaccuracy of a signal model brings about two specific problems: the separation of water and fat is inaccurate, and methods designed to estimate T_2^* in the presence of fat to do incorrectly in tissues containing fat [30]. Therefore, MPD methods are preferred over the 2P and 3P variants, when more accurate water and fat separation is required. The first MPD method (four-point Dixon – 4PD) was presented by Glover [12]. This method provides the possibility to measure the spectral width of the fat resonance. Yu et al. [30] introduced a novel MPD method for more accurate water and fat separation with multifrequency fat spectrum modeling, which was made possible thanks to a multi-peak signal model. The 2PD and 3PD methods assuming that both water and fat have a single resonant frequency have been found sufficient in many clinical applications, and have shown that excellent water-fat separation can still be achieved.

This article aims to introduce a novel Dixon method called Fast Triple-Spin-Echo Dixon (FTSED) where the measurement time is significantly reduced compared to other published FSE approaches for Dixon acquisition [29,38]. The presented method is not as fast as the method (fTED) introduced by Ma et al. [37], but on the other hand, the minimal echo spacing is not so limited as in fTED method. At 9.4 T, the water-fat frequency difference of 1400 Hz would require a hardly feasible echo spacing of 357 μs. The primary aim of the proposed method is the acquisition of several images with specific phase shifts between water and fat image components, encoded during one scan without prolonged measurement time compared to original FSE method [41]. The acquired data were reconstructed by iterative least-squares estimation method [28]. The proposed method FTSED [42] was implemented on a 9.4 T MRI (Bruker, BioSpec 94/30).

2. Method

The Fast Triple-Spin-Echo Dixon Sequence (FTSED) is 3PD method derived from the conventional fast spin-echo (FSE) method as proposed by Hennig et al. [41]. The FTSED method assumes the simple signal model with a single resonance frequency of fat. Fig. 1 shows the FTSED sequence providing echo time shifts of 0, 357 and 714 μs within the sequence, which at 9.4 T result in phase shifts of 0, π and 2π between water and fat. However, the echo shifts can be chosen in principle arbitrarily (within the limits of the sequence). The inserted delays will be different for odd and even number of inversion RF pulses (Fig. 2) to ensure water-fat phase shits 0, π and 2π, respectively. The water-fat phase shifts are achieved by inserting short delays after first and second portion of 3 spin echoes, as is shown in Fig. 1. These n echoes cover 3 k-space lines of the same image. However, the following 3 spin echoes culminate at the moment when water and fat are phase shifted with respect to each other appropriately to the inserted delay, and are assigned to another image. The last 3 spin echoes culminate when water-fat phase shift is equal to 2π, or in-phase. The main proposed method (FTSED) contains 2 delays, which results in three defined water-fat phase shifts and 3 × 3 echoes acquired per excitation (Fig. 1) for this case. The (Fig. 2) shows the theoretical necessity of k-space lines correction in the middle echo image; but practically, the correction is not required due to the fact that + π and − π shifts are indistinguishable. The sequence of phase encoding gradient steps (Fig. 1) for

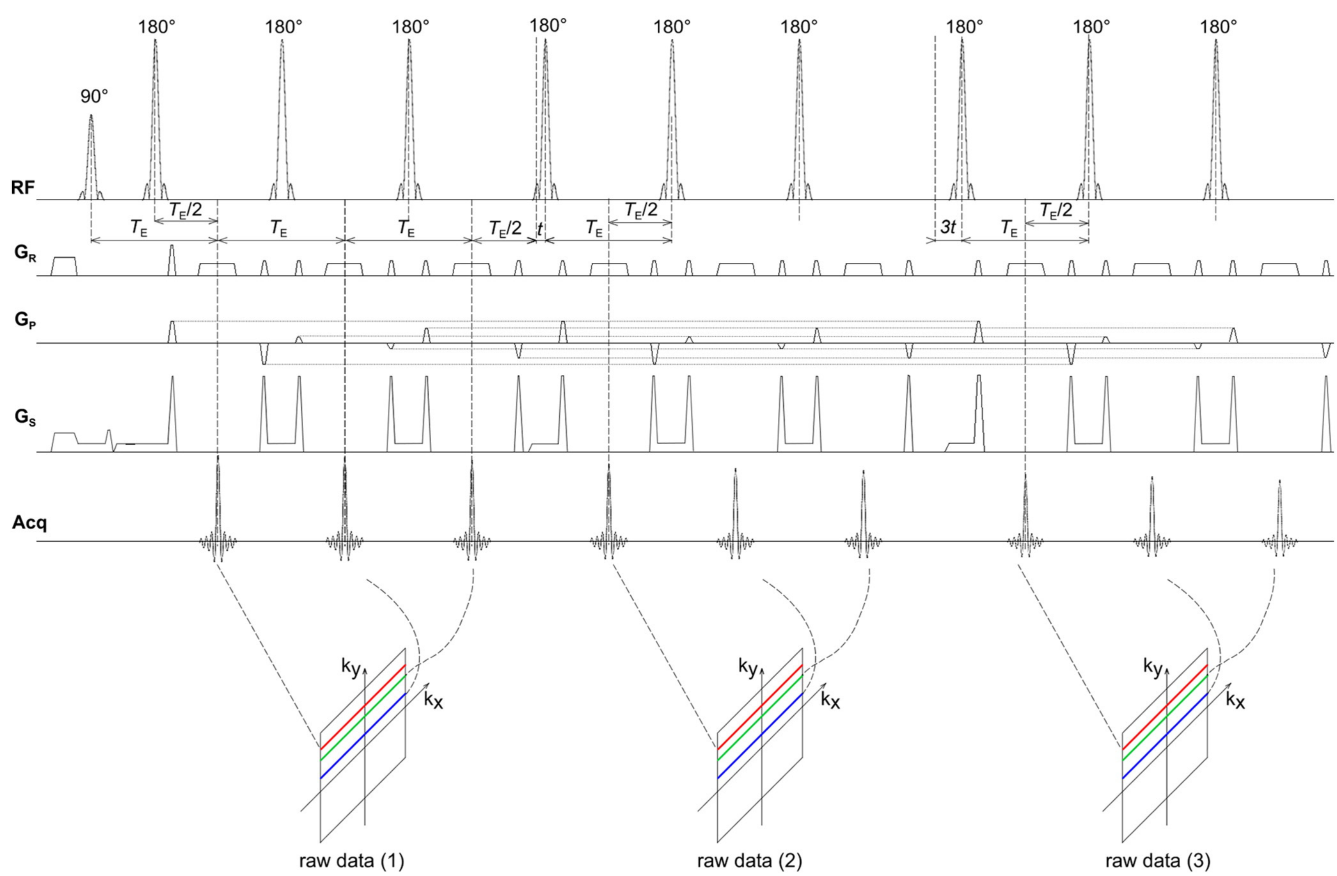

Fig. 1. The time diagram of the Fast Triple-Spin-Echo Dixon pulse sequence for a particular phase encoding scheme (0, − π, − 2π) or (0, π, 2π); echo train length ETL = 9, FTSED-factor = 3, t = 357 μs. Gradient G_R includes readout gradients and FID spoilers around refocusing pulses, G_P is the phase encoding, balanced in each interpulse period, and G_S is the slice selection gradient equipped with FID spoilers again. Three raw data sets are obtained during a single acquisition FTSED-factor = 3. The manner of k-space filling is same for each raw data set.