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Multispectral 3D phase-encoded turbo spin-echo for imaging near metal: Limitations and possibilities demonstrated by simulations and phantom experiments

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ABSTRACT

To see improvements in the imaging performance near biomaterial implants we assessed a multispectral fully phase-encoded turbo spin-echo (ms3D-PE-TSE) sequence for artifact reduction capabilities and scan time efficiency in simulation and phantom experiments.

For this purpose, ms3D-PE-TSE and ms3D-TSE sequences were implemented to obtain multispectral images (±20 kHz) of a cobalt-chromium (CoCr) knee implant embedded in agarose. In addition, a knee implant computer model and the acquired ms3D-PE-TSE images were used to investigate the possibilities for scan time acceleration using field-of-view (FOV) reduction for off-resonance frequency bins and compressed sensing reconstructions of undersampled data. Both acceleration methods were combined to acquire a +10 kHz frequency bin in a second experiment.

The obtained ms3D-PE-TSE images showed no susceptibility related artifacts, while ms3D-TSE images suffered from hyper-intensity artifacts. The limitations of ms3D-TSE were apparent in the far off-resonance regions (±[10–20] kHz) located close to the implant. The scan time calculations showed that ms3D-PE-TSE can be applied in a clinically relevant timeframe (~12 min), when omitting the three central frequency bins. The feasibility of CS acceleration for ms3D-PE-TSE was demonstrated using retrospective reconstructions before combining CS and rFOV imaging to decrease the scan time for the +10 kHz frequency bin from ~10.9 min to ~3.5 min, while also increasing the spatial resolution fourfold. The temporally resolved signal of ms3D-PE-TSE proved to be useful to decrease the intensity ripples after sum-of-squares reconstructions and increase the signal-to-noise ratio.

The presented results suggest that the scan time limitations of ms3D-PE-TSE can be sufficiently addressed when focusing on signal acquisitions in the direct vicinity of metal implants. Because these regions cannot be measured with existing multispectral methods, the presented ms3D-PE-TSE method may enable the detection of inflammation or (pseudo-)tumors in locations close to the implant.

1. Introduction

The incidence of knee and hip replacements [1,2] but also of trauma related procedures, have been steadily increasing in recent years. With the increasing number of metal implants, there is a growing need for accurate imaging in patients with substantial implants. There is an unmet medical need for imaging around implants and the assistance in frequently complex diagnostic dilemmas. Ideally, the soft-tissue contrast of MRI is exploited for the detection of complications [3–8] (e.g. osteolysis, infection, implant loosening, pseudo-tumors) [9,10] near metal implants.

To accurately perform post-operative MRI, multispectral turbo spin-echo (msTSE) techniques (e.g. MAVRIC, SEMAC) have been developed for metal artifact reduction caused by the paramagnetic nature of the implants [5,6,11]. To a large extent these methods have been successful in improving the diagnostic image quality surrounding metal implants. However, in the case of extreme susceptibility induced field gradients, equal or larger than the frequency encoding readout gradient, such techniques still result in signal hyper-intensities and signal voids [12]. In a recent study it was calculated that multispectral techniques are fundamentally limited in regions close to the implants where metal induced off-resonance offsets exceed ±12 kHz, when applied as in the clinic [13].

To overcome these remaining fundamental limitations, fully phase-encoded techniques have been suggested [14–16]. These techniques

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result in geometrically undistorted images, while also acquiring a densely sampled temporal signal decay curve that can be exploited for detailed signal decay characterization. The main limitation of these sequences is the inherently long acquisition time, requiring significant scan time acceleration before clinical application is feasible. In recent studies, both parallel imaging [14] and compressed sensing (CS) [15] have been combined with phase-encoded turbo spin-echo sequences to reduce the scan time of phase-encoded MRI techniques under 10 min for a single measurement. The peak B_1 requirements in 3D phase-encoded turbo spin-echo (3D-PE-TSE) acquisitions, however, limit the achievable refocusing bandwidth in a single acquisition to ~3 kHz after bandwidth optimization [15]. This results in incomplete signal excitation when imaging near strong paramagnetic alloys (i.e. cobalt-chromium, stainless steel).

In order to obtain 3D-(PE-)TSE images from a larger frequency range than the achievable rf refocusing bandwidth, multispectral excitation schemes are required [5,6]. Methods that utilize these multispectral excitation schemes, such as MAVRIC and SEMAC, cover the desired frequency range by repeating the imaging experiment with different rf offset frequencies. Coverage of the desired frequency range requires multiple 3D-PE-TSE acquisitions and dedicated multispectral excitation schemes [5,17] that will significantly increase the scan time.

To address scan time issues in ms3D-PE-TSE, both the number of required acquisitions as the number of phase encoding steps in each acquisition should be considered. By optimizing the refocusing bandwidth and the step size between rf pulses, it is possible to reduce the required number of acquisitions, while the scan time of the individual acquisitions can be reduced by adjusting the field-of-view (FOV) based on the excited signal locations. In the case of orthopedic implants the off-resonance signal is located close to the metal components of the implant, allowing for FOV reduction without introducing aliasing artifacts. Such time-saving FOV reductions have already been applied successfully for the MAVRIC sequence in two phase-encoded dimensions [5], while a FOV reduction in three dimensions might be possible for 3D phase-encoded imaging.

To assess the potential of multispectral 3D phase-encoded turbo spin-echo (ms3D-PE-TSE) for clinical applications, a better understanding of the artifact reduction capabilities and scan time limitations is required. Currently, the frequency coverage of multispectral methods is restricted to ±[8–12] kHz, because the extreme susceptibility gradients outside this range prevent accurate spatial encoding with frequency-encoded methods. Phase-encoded methods, however, are in principle unaffected by the extreme metal induced susceptibility gradients at these frequencies. To compare the artifact reduction capabilities of multispectral frequency-encoded and phase-encoded methods it is necessary to include off-resonance frequency bins that are excited with rf offsets larger than ±12 kHz.

In the study reported here, the primary goal was to identify if multispectral 3D phase-encoded turbo-spin-echo (ms3D-PE-TSE) can add value to existing multispectral 3D-TSE (ms3D-TSE) methods based on artifact reduction and required scan time requirements. For this study, a cobalt-chromium (CoCr) knee implant phantom and a CoCr knee implant computer model were used to study the imaging performance using a paramagnetic material that is often encountered in orthopedic imaging. First, ms3D-TSE and ms3D-PE-TSE sequences were implemented by designing multispectral excitation schemes using rf pulses with the same shapes, allowing a fair comparison between both methods. Both sequences were used to obtain multispectral images of the CoCr phantom from an extended frequency range of ±20 kHz for comparison of the artifact reduction capabilities. Second, the knee implant computer model was used to calculate the susceptibility induced field shift from the implant. The field shifts were used to determine the locations where the spatial encoding process of frequency-encoded imaging is expected to be fundamentally limited and to calculate the achievable FOV reduction factors in ms3D-PE-TSE. In addition to reduced FOV imaging, the use of CS acceleration for scan time reduction of ms3D-PE-TSE was demonstrated for the full frequency range by retrospective reconstructions. The calculated scan time for a far off-resonance bin of +10 kHz was experimentally confirmed in a second experiment, by combining reduced FOV imaging with CS acceleration [15,18]. The temporal signal of the phase-encoded techniques was exploited during data analysis (i.e. SNR adjustments, adjusting T_2^* weighting).

2. Methods

2.1. Implementation of multispectral imaging sequences

To facilitate a fair comparison between multispectral frequency-encoded imaging and multispectral phase-encoded imaging, ms3D-TSE and ms3D-PE-TSE sequences were implemented using similar pulse shapes on a clinical MRI system. The slice selection gradients were disabled in all sequences to exclude slice related artifacts in the data, and prevent mixing of slice distortions and frequency encoding related artifacts. The details of the original 3D-PE-TSE sequence are described in [15].

To implement a multispectral excitation scheme with a uniform intensity profile over the full multispectral frequency range, it is necessary to first choose a pulse pair and then determine the rf step size that result in the lowest intensity variation after combination of all frequency bins. For ms3D-PE-TSE the time-efficiency is the most important aspect to take into account when choosing the rf pulse pair. To maximize the time-efficiency of ms3D-PE-TSE, both a high rf bandwidth and short durations for the refocusing pulse are desired. In light of these criteria we chose to combine a 2.016 ms sinc-gauss excitation pulse with a 0.3456 ms block refocusing pulse to obtain a truncated sinc frequency profile with a FWHM of ~3 kHz [17]. For the ms3D-TSE sequence the rf bandwidth was decreased to ~2 kHz to limit the maximum signal displacement to ±1 pixel for a gradient strength of 1 kHz/pixel (according to $x' - x = \Delta v_0(x)\, 2\pi / \gamma G_{read}$). To this end, pulse lengths of 2.91 ms (the sinc-gauss excitation pulse) and 0.5 ms (the block refocusing pulse) were used in the ms3D-TSE sequence.

After choosing the pulse-pair, the rf step sizes (Δf) with the lowest intensity variations after sum-of-squares combination were determined using 1D Bloch simulations [19]. First, the actual frequency profiles of the ms3D-TSE and ms3D-PE-TSE the pulse-pairs were simulated for a [−20:0.02:20] kHz range with 100 μs time steps (code available on http://www-mrsrl.stanford.edu/~brian/bloch/). Second, the signal response over the total frequency range was determined by combining multiple rf frequency responses with a varying rf step sizes Δf of [1.0:0.01:3.0] kHz, followed by a sum-of-squares combination for each Δf. The Δf values with the most uniform signal response were selected (Fig. 1).

2.2. Magnetic field simulations

A 3D vectorized computer model of the femoral component of a knee implant (Smith & Nephew, UK) was used to calculate the susceptibility induced field distribution at 1.5 T and 3 T [20,21]. First, the 3D vector model was converted to a discrete susceptibility distribution ($d\chi_{CoCrMo} = 1300$ ppm [22]) in a grid coordinate system ($FOV = 128^3$ mm^3, voxel $= 0.25^3$ mm^3). The expected field shift was calculated using efficient forward 3D field calculations. Based on these calculations, all voxels with a calculated frequency value within the routinely applied frequency range of ±12 kHz were selected to detect the rf limited regions in current ms3D-TSE methods (Fig. 2).