Compressed sensing accelerated broadband 3D phase encoded turbo spin-echo imaging for geometrically undistorted imaging in the presence of field inhomogeneities

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Purpose: To obtain geometrically undistorted MR images in the presence of off-resonance effects in an acceptable time frame

Introduction: Field inhomogeneities have detrimental effects in conventional magnetic resonance imaging (MRI) and can degrade the image quality by geometrical distortions, signal misregistration, signal dephasing and incomplete excitation. Off-resonance effects originating from magnetic susceptibility differences within the subject (e.g. interventional devices, orthopedic implants, contrast agents) constitute a serious obstacle when accurate spatial localization is required[1]. In this study, we explore the potential of purely 3D phase encoded spin-echo (3D-PE-SE) sequences to produce geometrically undistorted images in a clinically acceptable timeframe. To achieve this goal a 3D-PE-SE is accelerated by combining turbo acceleration[3] and compressed sensing[4] by implementing a 3D-PE-TSE sequence with broadband rf pulses and dedicated undersampling patterns.

Methods: *Objects:* A grid phantom containing a titanium implant ($\Delta\chi$=182ppm) and a healthy volunteer with titanium screws in the knee were scanned to investigate the performance of the CS 3D-PE-TSE sequence.
Pulse sequences: A multi-spectral 3D-SE (ms3D-SE)[2], 3D-PE-SE and 3D-PE-TSE sequence were implemented on a 1.5T MR system (Philips, Best, The Netherlands). For the 3D-PE-TSE scan the flip angle of the first refocusing pulse was increased to ((180+α)/2), where α is the desired refocusing flip angle, to reduce oscillations in the signal amplitude over the echo train[5]. For standard block pulses and a $B_{1,max}$ of 23µT a bandwidth up to 3.5 kHz could be achieved. The acquisition parameters are indicated in table 1. The 2D-TSE, 3D-(ms)SE and CT images act as references.

Table 1: Acquisition parameters

Scan	Fig	Voxel (mm)	BWgr (Hz/pix)	BWrf (kHz)	Time (min)	Accel. factor
SE	2a	2x1.5x5	505	5.0	3.5	
msSE	2b	2x1.5x5	505	1.7	17.5	
msSE	2c	2x1.5x5	1011	1.7	17.5	
PE-SE	2d,3a	2x1.5x5		5.0	436	0
PE-SE	3b	2x1.5x5		5.0	73	6
PE-TSE	3c	2x1.5x5		2.9	21.8	20
PE-TSE	3d	2x1.5x5		2.9	7.3	60
TSE	4b	1.3x1x1.3	218	2.9	3.5	
TSE	4c	1.3x1x1.3	218	2.9	3.5	
PE-TSE	4d	1.3x1x1.3		2.9	19.8	60
PE-TSE	4e	1.3x1x2.5		2.9	9.8	60

Sampling pattern design: A 3D spherical sampling pattern with a stepwise T_2 weighting was obtained by sorting the k-space coordinates in spherical layers each corresponding to a certain echo number and consisting of an equal number of points (fig 1). All sampling points in a certain layer are therefore sampled at the same 'echo time' and have an equal T_2 weighting. Variable density undersampling patterns for CS-TSE accelerated imaging were designed in a similar fashion.

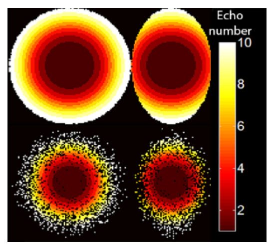

Fig 1: Sampling patterns for 3D-PE-TSE data with a spherical shutter (top row) and CS acceleration (bottom row). The kx-ky (left) and ky-kz plane (right) through the center of k-space are shown for an acquisition matrix of 96x96x64, which was used to acquire fig 4.

CS reconstruction: A non-linear conjugate gradient solver[4] was used to minimize $\lambda_w||\psi_w m||_1+\lambda_{TV}TV(m)$, where $||\psi_w m||_1$ is the L_1 norm regularization in the wavelet transform domain and TV(m) a total variation regularization in the image domain with weighting factors λ_w and λ_{TV}. The original 2D regularizations were replaced with a 3D wavelet (Daubechies 6) L_1 norm regularization (λ_w) and a 3D total variation norm regularization (λ_{TV}) to reconstruct the 3D-PE-(T)SE data with three undersampled dimensions.

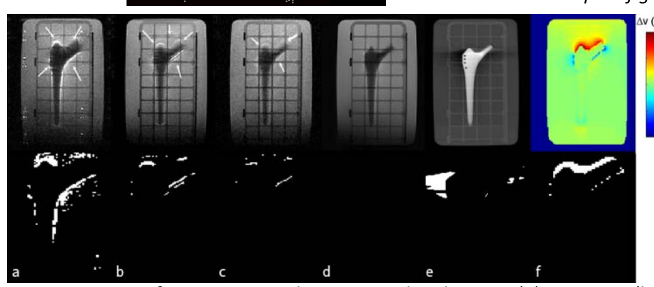

Fig 2: Images of a titanium implant acquired with 3D-SE (a), ms3D-SE (b,c), 3D-PE-SE (d) and CT (e) plus a field offset map (f). The bottom row highlights hyper- (a-d) or hypointense (e) voxels and regions with Δv>1kHz off-resonance (f).

Results: The spatial encoding of 3D-PE-(T)SE was unaffected by susceptibility induced off-resonance effects (fig 2d,3), which did cause geometrical distortions and/or signal hyper-intensities in broadband 3D-SE (fig 2a) and, to a lesser extent, in ms3D-SE (fig 2b,c). The CS-TSE combination resulted in an overall acceleration factor of 60 (fig 3), decreasing the original 3D-PE-SE scan time from 7 hours (fig 3a) to 7 minutes (fig 3d) at the cost of some blurring. CS accelerated 3D-PE-TSE *in vivo* images of a titanium screw acquired in 20 (fig 4d) and 10 minutes (fig 4e) produced geometrically undistorted images unlike conventional 3D-TSE (fig 4b-c).

Discussion: This work demonstrates the feasibility to obtain geometrically accurate images near severe field inhomogeneities in acceptable timeframes. The current method may be applied in fields that require high spatial fidelity such as orthopedic imaging, hybrid MR imaging methods and radiotherapy.

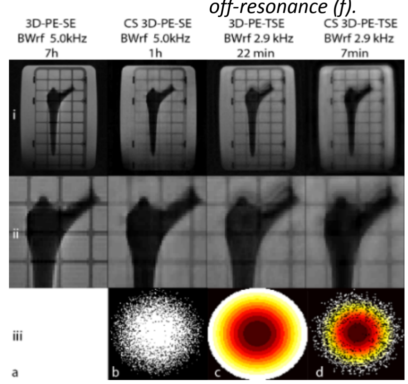

Fig 3: Fully sampled (a,c) and CS (b,d) images of a titanium implant (i,ii) acquired with 3D-PE-SE (a,b) or 3D-PE-TSE (c,d) and the sampling pattern in kz=0 (iii) are shown.

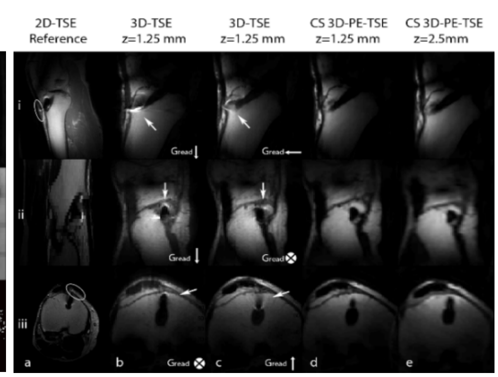

Fig 4: In vivo mages of a titanium screw in the knee acquired with 2D-TSE(a), 3D-TSE (b,c), 3D-PE-TSE (d,e) reformatted in three orientations (i-iii). The micro coil is indicated in (a,i) and (a,iii).

References: 1. C.J.G. Bakker, Magn. Reson. Imaging 31 p86-95 (2013), 2. K.M. Koch, Magn. Reson. Med. 61 p381-390 (2009), 3. N.S. Artz, Magn. Reson. Med. 71 p681–690 (2013), M. Lustig, Magn. Reson. Med. 58, p1182–1195 (2007), 5. Alsop, Mag. Reson. Med. 37 p176-184