Acceleration of multi-echo spin-echo imaging for T2 mapping using single or multiple coils

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Introduction: The measurement of T_2 with a multi-echo spin-echo sequence is associated with a long acquisition time and a high SAR due to the use of a train of 180° RF pulses and a long TR [1]. Parallel acquisition techniques such as SENSE [2] or GRAPPA [3] allow a reduction of the number of phase encoding steps. However, their main limiting factor is, besides the number of available receive channels, the rapid decrease in SNR for higher acceleration factors. This work presents an alternative acceleration method that exploits the temporal correlation of the *k*-space signal at different echo times. It is based on a reconstruction algorithm that was presented in [4]. Here, an extension to the case of multiple coils is presented, and the approach is evaluated with respect to SNR and reconstruction artefacts.

Theory: The *k*-space sampling pattern proposed in [4] was implemented as shown in Fig. 1. Let R be the desired acceleration factor. Each spin-echo is straddled by its own phase-encoding and rewinder pair. During the echo train, the amplitude of the phase-encoding gradient is modified gradually to introduce a shift in *k*-space of Δk, $2\Delta k$… $(R-1)\Delta k$ between the first and the $(R-1)$ consecutive echoes. After a cycle of R echoes, the gradient takes its initial value, and the next cycle starts. With that sub-sampling pattern, the number of phase-encoding steps is reduced by the factor R. The central part of *k*-space is acquired with full sampling for calibration purposes. The non-measured *k*-space data $S_t(k)$ are then estimated by means of a linear combination of neighbors in the *kt*-space [4]:

$$\hat{S}_t(k)=\sum_{\tau=-n_\tau}^{n_\tau}\sum_{\kappa=-n_k}^{n_k} w_{\tau,\kappa}S_{t+\tau}(k+\kappa) \tag{1}$$

The coefficients w of the reconstruction kernel are estimated on the basis of the calibration samples.

We now consider the case of signal acquisition with an array of N_c coils. Since the relaxation process is identical for all coil signals, the same kernel can be used to reconstruct each coil image separately. Moreover, all coil calibration signals S^{cal} can be included in the least-squares fit of the coefficients w:

$$(\hat{w}_{\tau,\kappa})=\arg\min_{w}\sum_{\gamma=1}^{N_c}\sum_{t,k}\left(S_{\gamma,t}^{cal}(k)-\sum_{\tau=-n_\tau}^{n_\tau}\sum_{\kappa=-n_k}^{n_k} w_{\tau,\kappa}S_{\gamma,t+\tau}(k+\kappa)\right)^2 \tag{2}$$

Thus, the reconstruction kernel reflects only the temporal correlation due to relaxation, and the estimation of its coefficients is improved by combining all coil signals. After Fourier transform, the reconstructed coil images can be described by the following expression:

$$\hat{s}_{\gamma,t}(x)=\sum_{u=0}^{R-1}s_t(x_u)c_\gamma(x_u)g_t(x,x_u)\quad\text{with } x_u=x+u\frac{FOV}{R} \tag{3}$$

c_γ is the coil sensitivity, and g_t models the *kt*-space reconstruction function in image space. Ideally, $g_t(x,x_u)$ is a Dirac function, which is nonzero only if $x=x_u$. Since the kernel w has a limited number of coefficients, $g_t(x,x_u)$ only approximates the Dirac function. Eq. (3) can then be inverted to yield an estimate of $s_t(x)g_t(x,x)$, which is a good approximation of the true signal $s_t(x)$. This inversion, as in SENSE, amounts to a multiplication with the sensitivity matrix $(C^HC)^{-1}C^H$.

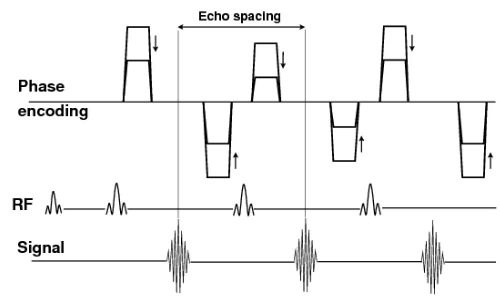

Fig. 1: Modified multi-echo spin-echo sequence, with varying gradient amplitudes, for R=2.

	(a) SENSE	(b) GRAPPA	(c) kt-T2	(d) MC kt-T2
R=2	0.0152	0.0143	0.0084	0.0075
R=4	0.0470	0.1421	0.0089	0.0080

Tab. 1: Mean normalized chi-squares of the fit residuals

Methods: Multi-echo spin-echo images for T_2 mapping in the brain (32 echoes, 8ms echo spacing, resolution: 1.2×1.2×8mm, TR=1000ms) were acquired with a 6 channel head-coil on a 1.5T scanner (Achieva, Philips Medical Systems). Acceleration factors R of 2 and 4 were applied, with respectively 4 and 8 calibration phase-encoding steps. The same data were reconstructed with (a) SENSE, (b) GRAPPA, (c) the *kt*-reconstruction applied separately to each coil (denoted *kt*-T2), and (d) the multi-coil *kt*-reconstruction (denoted MC *kt*-T2*)*. GRAPPA and both *kt*-algorithms used the same calibration data. A reference scan was performed to measure the coil sensitivities required for SENSE and MC *kt*-T2. T_2 maps were computed by means of a non-linear least squares algorithm. Maps of the chi-square of the fit residuals were computed as an intrinsic measure of the reconstruction quality, since deviations from the exponential decay reflect both noise amplification and remaining folding artefacts.

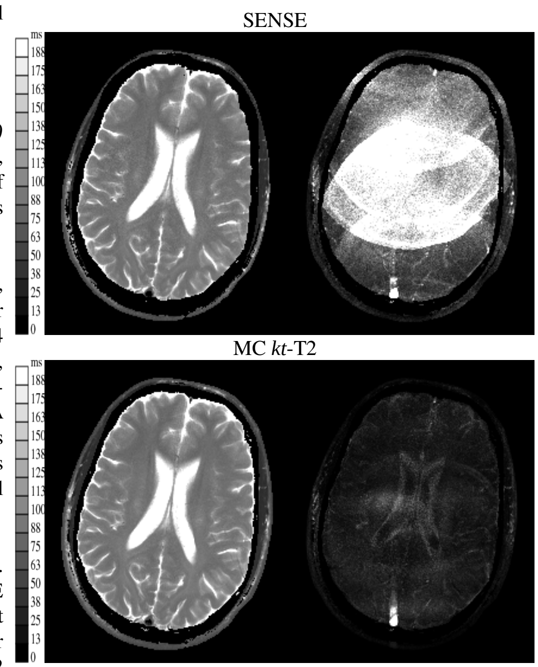

Fig. 2: T_2 and chi-square maps obtained with SENSE and the proposed multi-coil *kt*-T2 algorithm for R=4.

Results and discussion: The mean normalized chi-squares of the fit residuals are listed in Tab. 1. Examples of T_2 and chi-square maps for R=4 are shown in Fig. 2. Images and maps obtained with SENSE are characterized by significant noise amplification, while those obtained with GRAPPA (images not shown) suffer from folding artefacts, especially for R= 4. Both *kt*-algorithms achieve superior reconstruction quality. Folding artefacts are almost completely removed with the multi-coil *kt*-T2 reconstruction. The *kt*-T2 methods make use of the redundancy in the multi-coil, multi-echo calibration signal to improve the estimation of the reconstruction kernel. This explains their better performance, as compared to GRAPPA, for the same number of calibration data.

Conclusion: The linearity of the relaxation signals in *kt*-space forms the basis of the proposed *kt*-T2 method, which, like *kt*-BLAST and *kt*-SENSE [5], exploits the temporal correlation of the MR signal to reduce the number of encoding steps. Interestingly, for single coil acquisitions, this represents a new way of reducing the scan time that was not accessible with sensitivity encoding approaches. For multiple coils acquisitions, this extends the existing methods and allows an appreciable improvement in reconstruction quality, limiting especially noise amplification.

References: [1] Bernstein (2004). [2] Pruessmann et al, MRM, 42:952–962 (1999). [3] Griswold et al, MRM, 47:1202–1210 (2002). [4] Sénégas et al, ISMRM, #1785 (2007). [5] Tsao et al, MRM, 50:1031–1042 (2003).