Indirect Echo Compensated T2 Mapping from Highly Undersampled Radial FSE Data with SERENADE

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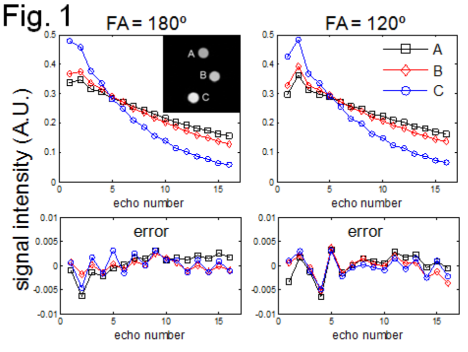
Introduction: There is an increasing interest in fast T2 mapping in the clinic. With that goal, a radial fast spin echo (radFSE) technique was developed (1). The method yields data with high spatial and temporal resolution for the reconstruction of T2 maps. As with all T2 mapping techniques based on multiple refocusing pulses, the accuracy of T2 estimation in this technique is compromised by the presence of indirect echoes (eg. stimulated echoes).

As an extension to the extended phase graph (EPG) model proposed by Hennig (2), Lebel and Wilman recently proposed a slice resolved extended phase graph (SEPG) algorithm for T2 estimation from decay curves contaminated by indirect echoes (3). However, the application of the SEPG algorithm to highly undersampled data is challenging. Although model-based algorithms have been proposed for highly undersampled radFSE data (4,5), incorporation of SEPG into the model results in a highly non-linear system which is difficult to solve. In this work a principal component approach is proposed to linearize a signal decay model that is composed of both direct (spin-echo) and indirect echoes. The proposed *SlicE Resolved ExteNded phAse graph baseD rEconstruction of principal component coefficient maps* (SERENADE) algorithm aims to provide accurate T2 estimates from highly undersampled data which can be acquired in a short period of time.

Fig. 1



Theory: According to the SEPG model, the signal intensity of a voxel at echo *j* with given I_0, T1, T2 and B1 field values can be written as (3):

$$C(I_0,T_1,T_2,B_1,\alpha_0(z),...,\alpha_j(z),j)=I_0\cdot\int_z EPG(T_1,T_2,B_1,\alpha_0(z),...,\alpha_j(z),j)dz \quad [1].$$

In Eq. [1], $\alpha_0(z)$ and $\alpha_j(z)$ (j=1, …, N) are the prescribed slice profile of the excitation and refocusing pulses along the z direction, respectively. $EPG(\cdot)$ is the EPG model in which the slice profile is not considered (2). Given the signal model in Eq. [1], a model-based reconstruction algorithm for highly undersampled data can be developed by extending the approach of (5) as:

$$\mathbf{I}_0,\mathbf{T_2},\mathbf{T}_1,\mathbf{B}_1=\arg\min_{\mathbf{I}_0,\mathbf{T_2},\mathbf{T}_1,\mathbf{B}_1}\{\sum_{J=1}^{N}\left\|FT\{C(\mathbf{I}_0,\mathbf{T_1},\mathbf{T}_2,\mathbf{B}_1,\alpha_0(z),...,\alpha_j(z),j)\}-\mathbf{K}_j\right\|^2\} \quad [2],$$

where $\mathbf{I}_0,\mathbf{T_2},\mathbf{T}_1,\mathbf{B}_1$ are the vectors containing the I_0, T2, T1 and B1 values of all voxels and $\mathbf{K}_j$ is the measured k-space data at j^th^ echo. Note that the cost function in Eq. [2] is highly nonlinear and it is difficult to calculate its gradient to use gradient-based minimization algorithms.

Table 1. T2 values (ms) obtained from highly undersampled data

Vial	Spin-Echo	FA = 180°		FA = 120°	
		Exponential fitting	SEPG fitting	Exponential fitting	SEPG fitting
A	**202.3**	215.7	**202.5**	244.2	**201.6**
B	**153.8**	165.1	**156.0**	181.9	**151.8**
C	**77.3**	83.0	**78.6**	90.8	**76.8**

To overcome this challenge, we propose SERENADE where principal components (PCs) are used to linearize the signal model in Eq. [1]. The PCs are obtained using a set of decay curves with indirect echoes generated according to Eq. [1] for expected ranges of T1, T2, B1 values and echo times. Let $\vec{v}$ be a vector representing a T2 decay curve with indirect echoes. Let L be the number of PCs to be used and $\vec{p}_i$ be the i^th^ PC. $\vec{v}$ can be approximated by: $\vec{v}=\sum_{i=1}^{L}m_i\vec{p}_i$, where m_i is the weighting of the i^th^ PC. $\hat{\mathbf{P}}=(\vec{p}_1,\vec{p}_2,\ldots,\vec{p}_L)$ is the matrix consisting of the vectors of the first L PCs. Let $\vec{M}_i$ be the vector of m_i for all the voxels and **M** can be formed as $(\vec{M}_1,\vec{M}_2,\ldots,\vec{M}_L)$. Let $\hat{\mathbf{P}}_j$ denote the j^th^ row of the matrix $\hat{\mathbf{P}}$. Note that $\mathbf{M}\hat{\mathbf{P}}_j^T$ yields the image at echo j from the L PC coefficients. Thus Eq. [2] can be reformulated as:

$$\hat{\mathbf{M}}=\arg\min_{\mathbf{M}}\{\sum_{j=1}^{N}\|FT_j(\mathbf{M}\hat{\mathbf{P}}_j^T)-\vec{\mathbf{K}}_j\|^2\}+\sum_i\lambda_i Penalty_i(\mathbf{M})\} \quad [3].$$

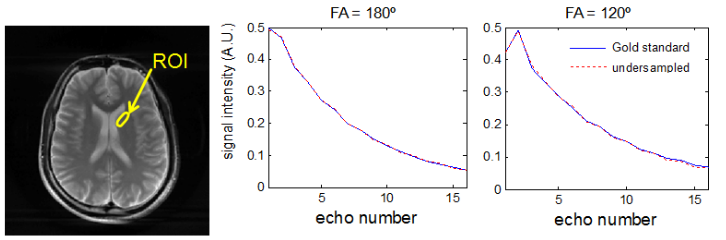


Fig. 2

	FA = 180°		FA = 120°	
	Gold standard	Undersampled	Gold standard	Undersampled
Estimated T2 by SEPG fitting (ms)	84.5	85.6	84.9	82.4

Since the cost function in Eq. [3] is now linear it can be efficiently solved by a conjugate gradient algorithm. The penalty terms in Eq. [3] are used to exploit the spatial compressibility in the framework of compressed sensing (4). The decay curves are reconstructed from $\hat{\mathbf{M}}$. SEPG fitting can be applied to the reconstructed curves to obtain T2 estimates as shown in (3).

Methods: Data for a phantom (composed of vials filled with $MnCl_2$ solutions) and brain were acquired on a 1.5T MRI scanner with the radFSE sequence. A total of 256 radial lines per TE were acquired for gold standard data, whereas 16 and 32 lines per TE were acquired for undersampled phantom and in vivo data. The ranges of T2 and B1 for PC training were 35-500 ms and 0.5-1.2, respectively. T1 was set to ∞ according to (3).

Results: The gold standard decay curves of the 3 vials in the phantom for two refocusing flip angles (FA) are shown in Fig. 1 (top). The error plots of the decay curves reconstructed from highly undersampled radFSE data by SERENADE are shown at the bottom. Note that the errors are small for all echo points and both FAs. T2 values obtained from highly undersampled data are shown in Table 1 for conventional exponential fitting and the SEPG fitting where the decay curves were generated by SERENADE. Note that the T2 estimates from exponential fitting vary up to 13% when the FA of the refocusing pulses decrease from 180° to 120°, whereas the variations of the T2 estimates yielded by SEPG fitting are <3% and agree very well with the T2 values obtained from spin-echo data.

Fig. 2 shows results for brain data. The ROI's decay curves reconstructed from highly undersampled data by SERENADE agrees well with the gold standard curves for both FAs. SEPG fitting on curves reconstructed by SERENADE yields similar T2 estimates for highly undersampled and fully sampled data regardless of variations in the FA of the refocusing pulse. It should be pointed out that the acquisition time for the gold standard (17 min) was significantly longer than for the undersampled data (2 min 12 sec).

Conclusion: We developed a novel SERENADE reconstruction algorithm to accurately reconstruct decay curves contaminated with indirect echoes from highly undersampled data. With this method accurate T2 estimates are obtained using rapidly acquired data. The T2 estimates from SERENADE are independent of FA which enables T2 estimation in high field strength magnets.

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References: 1.Altbach M, et al. MRM 54(2005); 2.Hennig J. JMR 78(1988); 3.Lebel RM, et al. MRM 64(2010); 4. Huang C, et al. MRM, in press; 5.Block KT, et al. IEEE-TMI 28(2009)