Efficient maximum likelihood estimation of T_1, T_2*, and flip angle error using variable-length echo trains in combined AFI and FLASH experiments

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Target Audience Researchers interested in sequences and algorithms for T_1, T_2^*, and flip angle mapping and researchers interested in Actual Flip Angle Imaging (AFI) and related experiments.

Purpose An experiment consisting of one AFI acquisition[1] and one FLASH acquisition[2] was previously demonstrated for high-accuracy T_1 and flip angle mapping[3]. In the present work we demonstrate the use of multi-echo AFI and FLASH with a high bandwidth and variable-length echo-trains in order to: 1) increase SNR/time by increasing the amount of time spent reading out data, 2) reduce spatial distortions due to B_0 inhomogeneity (as was previously done for multi-echo MPRAGE[4]), and 3) estimate T_2^* from the resulting echo train. The use of multi-echo data requires no increase in scan time, but significantly increases the amount of data that must be processed. An algorithm is presented that can fit multi-echo image data in less than 1 ms/voxel with our current single-threaded C++ implementation, more than 50× faster than the previously published fitting algorithm for single-echo data[3].

Methods AFI uses a gradient echo readout with an alternating steady state produced by using a consistent pulse (α_{AFI}) and interleaving two TRs ($\mathrm{TR}_{\mathrm{AFI,1}}, \mathrm{TR}_{\mathrm{AFI,2}}$). In our experiment we paired a 3D AFI sequence with $\alpha_{AFI} = 40°$, $\mathrm{TR}_{\mathrm{AFI,1}} = 10$ ms, $\mathrm{TR}_{\mathrm{AFI,2}} = 100$ ms with a 3D FLASH scan having $\alpha_{\mathrm{FLASH}} = 10°$ and $\mathrm{TR}_{\mathrm{FLASH}} = 10$ ms. Both volumes had a matrix size of $64 \times 44 \times 64$ and a 4 mm isotropic resolution (to reduce imaging time without using parallel acceleration), 500 Hz/px bandwidth, a minimum TE of 1.56 ms, and echo spacing of 2.1 ms. Each TR was filled with as many echoes as would fit (capped at 12 due to a technical limitation in our experimental sequence), giving 3 echoes in the FLASH and shorter AFI TR, and 12 echoes in the longer AFI TR. Our multi-echo AFI sequence used gradient spoiling equal to 5× the area under the readout gradient in the short TR, and 50× the area during the long TR, while our FLASH scan used 5× gradient spoiling. Both sequences used an RF spoiling increment of 129°.[5] Each scan had 10 seconds of dummy TRs to reach steady state, giving total scan times of 5:38 (AFI) and 0:38 (FLASH). An additional noise-only scan (no RF-pulses) was acquired with matched readouts for 18 s.

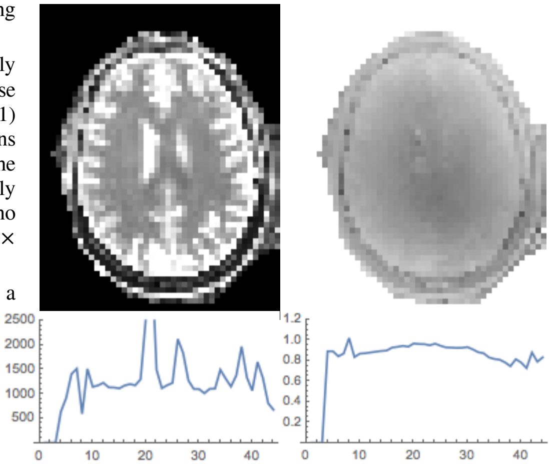

Fig 1. (*top*): Representative slice from estimated parameter volumes: T_1map (*left*), and flip angle error scale map (*right*). (*bottom*): Plots of values along middle row of images. The clipped T_1 peak in the ventricle reached 5s.

One human volunteer, having given informed consent, was scanned in a 3 T TIM Trio (Siemens Healthcare, Erlangen, Germany) using the product 32-channel head matrix. Raw data was copied off the scanner and processing was performed using custom C++ software on a laptop with an Intel Core i7 CPU. k-space from each TR/echo/channel was transformed via 3D inverse Fourier transform to produce one complex image for each TR/echo/channel. The channel covariance matrix was estimated from the noise-only scan and used to "pre-whiten" the noise in the complex images, producing the same number of "whitened" output channels but now with an identity covariance matrix. The fitting algorithm operates independently on each voxel in our whitened data, and performs two steps:

1. Create a matrix of measurements with TR/echo along the columns and channels along the rows. The first left singular vector of this matrix is an estimate of the "true" signal without B_1^- weighting.
2. Treating the output of step 1 as a single-channel measurement, the maximum likelihood estimator of T_1 and flip angle scaling error κ (*e.g.,* expressed as an RMS error[3]) is also the maximum of

$$\epsilon(\mathrm{T}_1,\kappa) = \sum_j \frac{\left|\boldsymbol{w}_j^T \boldsymbol{q}(\mathrm{T}_1,\kappa)\right|}{\sum_i \delta_{i,j}[q_i(\mathrm{T}_1,\kappa)]^2}$$

where i indexes the three TRs (2 AFI + 1 FLASH) and j indexes echoes, $\boldsymbol{q}(\mathrm{T}_1,\kappa)$ is a real-valued 3-vector representing the forward model for the noise-free signal that would be observed in each of the three TRs given the parameters, $\boldsymbol{w}_j^T$ is the complex-valued 3-vector of measured data for the j^{th} echo (with 0 for TRs that do not include the j^{th}echo), and $\delta_{i,j}$ is an indicator that is 1 if the i^{th} TR includes the j^{th} echo and 0 otherwise. In our experiment, we found that for any choice of fixed T_1, $\epsilon_{\mathrm{T}_1}(\kappa)$ increases monotonically to the maximum κ over a wide region of parameter space, and similarly for fixed κ, $\epsilon_\kappa(\mathrm{T}_1)$ increases monotonically to the maximum T_1. From this observation, we can do a Fibonacci search of $\mathrm{T}_1 \in (50\ \mathrm{ms}, 10\ \mathrm{s})$ at 1 ms resolution, at each step setting the error function to be $\epsilon_{\mathrm{T}_1}(\kappa)$ and then doing an inner Fibonacci search of $\kappa \in (0.1, 2.5)$ at 10^{-6} resolution to evaluate the maximum of $\epsilon_{\mathrm{T}_1}(\kappa)$. We found this hierarchical search to be efficient and reliable for this fitting problem.

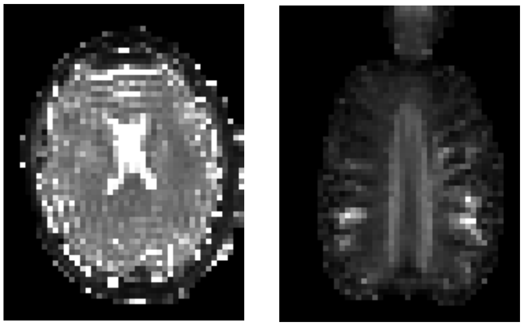

Fig 2. Representative slice from estimated T_2^* volumes: Human subject (*left*), and pineapple (*right*). The human has longer $\mathrm{T}_2^*$and shows ringing, perhaps due to incomplete spoiling or insufficient echo train length. The pineapple, with shorter T_2^*, is well fit by the sequence, showing the core and outer structure.

Single-exponential T_2^* fitting was performed in Mathematica (Wolfram Research, Champaign, IL, USA) on the longest echo train using the SVD-combined data.

Results and Discussion A representative slice is shown in Fig. 1. Although the images are low-resolution, the results are plausible and appear consistent throughout the head. Despite estimating each voxel independently, the resulting flip angle scale error map is smooth save for some artefacts in the ventricles, indicating that our high-bandwidth multi-echo readout has been well fit by the model. We have also generated a T_2^* map, shown in Fig. 2. In the human subject we observed a ringing artifact, and so we repeated the same experiment with a pineapple (having shorter T_2^* than the human but similar T_1). The results in the pineapple are of high quality, and so further investigation is needed to determine the cause; perhaps the echo train is too short, or spoiling is incomplete as this is known to be an issue in AFI.[5]

Conclusions We have demonstrated a novel multi-echo AFI+FLASH experiment that improves SNR/time, reduces susceptibility distortion, and allows us to generate a T_2^* map at no additional scan time cost. We have also demonstrated a novel fitting algorithm that is very efficient and works with both single- and multi-echo AFI+FLASH data. While the current results are low-resolution, scaling up to higher resolutions will simply require longer scan time. By increasing SNR/time through adding echoes, we can make up some of the SNR that will be lost through the use of parallel acceleration to reduce scan time.

References [1] Yarnykh et al. (2007) MRM 57:192-200 [2] Haase et al. (1986) JMR 67(2):258-266 [3] Hurley et al. (2012) MRM 68:54-64 [4] van der Kouwe et al. (2008) NeuroImage 40(2):559-569 [5] Nehrke (2009) MRM, 61:84-92

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