Real time shimming for compensation of respiration induced field changes

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Introduction

On of the limitations of MRI of brain at high field are respiratory cycle related Bo field fluctuations [1,2]. Depending on the imaging technique, this can result in a variety of image artifacts include ghosting, blurring, and subtle image shifts. In principle, the fluctuations can be compensated for by real-time field correction or post-hoc correction based on e.g. navigator echoes. However, one complication is that the Bo effect is spatially varying, which means that a global correction might not be adequate [3,4]. In order to overcome this issue, we propose a system for real time (RT) shimming, which modulates NMR frequency, as well as linear and higher order shims as function of the respiration state.

System and Methods

The RT-shimming was implemented on a GE 7T with Resonance Research Inc. (RRI) higher order shim amplifiers. A computer was added (from RRI) with 9 DAC channels, for fo, x,y,z and 5 second order shims. The shim terms are added to the static shim settings at the amplifiers. For the linear terms (x,y,z), the gradient amplifiers were modified (by GE) to provide a second input through a summing amplifier, which adds independently to the normal waveform input. For the fo compensation the reference synthesizer for the downconverters was switched to FM mode, where the frequency modulation is controlled by the DAC. The RRI computer is driven over a serial link by a control computer, which also receives the respiratory signal from the scanner (using the standard GE bellows, 4 ms sample time), and the scanner trigger signals.

Each channel was calibrated by mapping its phase effects in an oil phantom using an EPI sequence (parameters: 96x72 voxels over 24x18 cm2, 12 2 mm slices with 8 mm gap, TE 30 ms, TR 1s). In a normal scan session, after localization and shimming, the effect of respiration on Bo is measured. For this training data the respiratory signal, the triggers (for timing) and an EPI time-series of 120 s are acquired (with the same parameters). The phase changes in this EPI time-series are then high pass filtered (>0.11 Hz) and correlated to the respiration signal. Subsequent scans can be compensated by calculating the appropriate shim changes as function of the respiratory signal in real time. The shims are updated every 80 ms. As a demonstration, one volunteer was scanned. After the training set, a 60 s EPI series was acquired with compensation, and gradient echo images were acquired with and without compensation.

Results

Obvious correlation (coefficient 0.98) is seen between the filtered phase time course of one voxel from the training set and the respiratory signal (Fig.1). The NMR signal lags by about 70ms with respect to the respiration. Fig. 2 shows the EPI phase time course with RT shimming, demonstrating the reduction in fluctuations compared to Fig. 1. The average SD of the filtered phase was 2.3 times lower with RT shimming. In Figs. 3,4 the effect of the compensation is shown on standard gradient echo MRI. A substantial reduction in ghosting is seen with RT shimming as compared to a scan without (Fig. 3). Fig. 4 shows a high resolution scan with RT shimming, and a simulation using the same data where k-space was recalculated with all shimming corrections inversed.

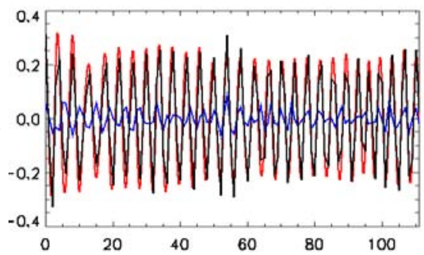

Fig. 1 Example of respiration waveform (red) and phase time course (black), blue is the difference

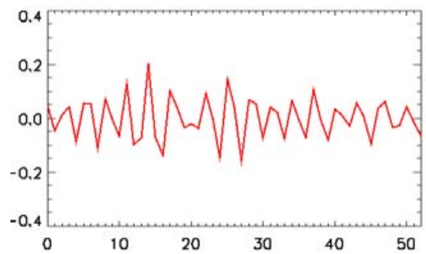

Fig. 2 Example filtered phase time course with compensation, plotted at the same vertical scale as fig. 1

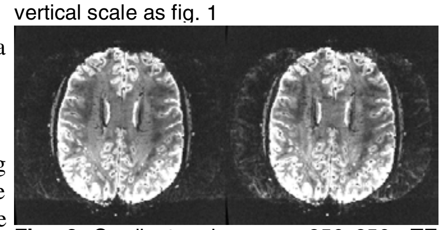

Fig. 3 Gradient echo scan 256x256, TE 20ms: left with, right without RT shimming.

Discussion

The EPI data shows that the phase stability can be markedly improved by the real time shimming system. The image quality of standard anatomical scans improves notably by using this system. The approach can be used for all types of scans, as no navigator of other sequence modifications are required. The method is important for high field MRI where the respiratory effects are larger. Also note at higher field strength T2* contrast is generally better than T2 contrast, making gradient echo imaging preferable. At lower fields, the frequency shifts are smaller, but for example in fMRI the optimal echo time and acquisition window are longer, so that the total phase changes can still be significant and this compensation system may be of use there as well. RT shimming, which calculates and adjust dynamic shim changes on the fly, differs from earlier proposed dynamic shimming methods [5,6], in the sense that there only static slice to slice shim differences are calculated a priori.

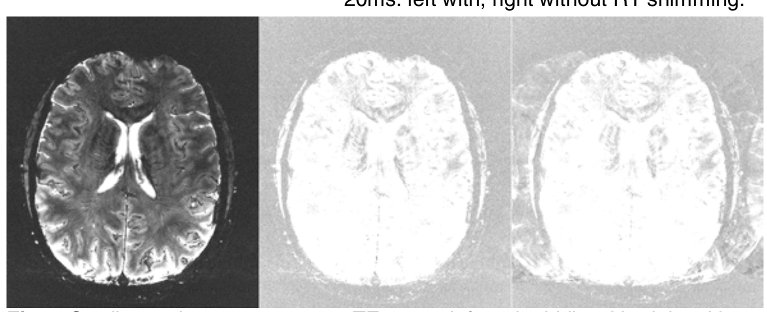

Fig 4. Gradient echo scan 512x384, TE 40ms: left and middle with, right without RT shimming (simulated). The scaling is increased to show the background.

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