Real Time Shimming for Compensation of Respiratory Field Changes

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The Problem

One of the limitations of MRI of the brain at high field is the respiratory cycle related B_0 field fluctuation [1,2]. An example of the resulting phase fluctuation is shown in Fig. 1. Depending on the imaging technique, this can result in a variety of image artifacts including ghosting, blurring, and subtle image shifts, see Fig. 2a. Some form of real-time or post-hoc correction based on e.g. navigator echoes is possible, however, the B_0 effect is spatially varying, as is apparent in Fig. 3, which means that a global correction might not be adequate [3,4]. We implemented a system for real time shimming (RTS), which modulates the B_0 frequency, as well as linear and higher order shims as function of the respiration [5]. The method allows for spatially varying field corrections and does not require any sequence modifications, making it compatible with all existing protocols.

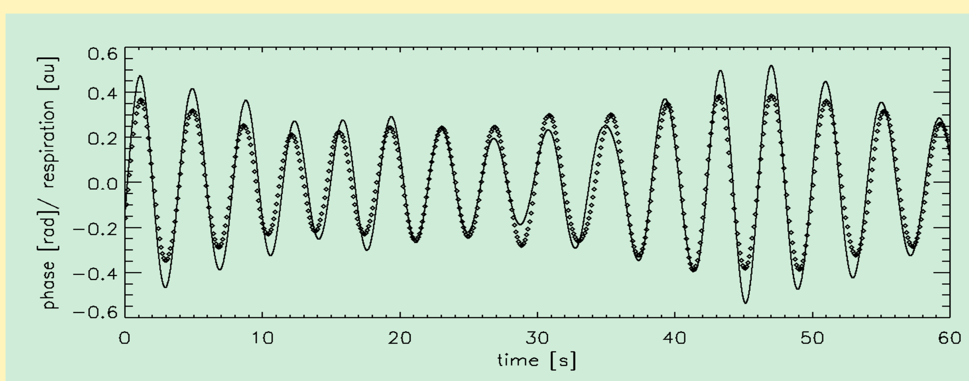

Figure 1. Chest position (line) and phase of one voxel (diamonds) over time in an EPI series with TE 30ms, TR 100ms. The signals are obviously correlated.

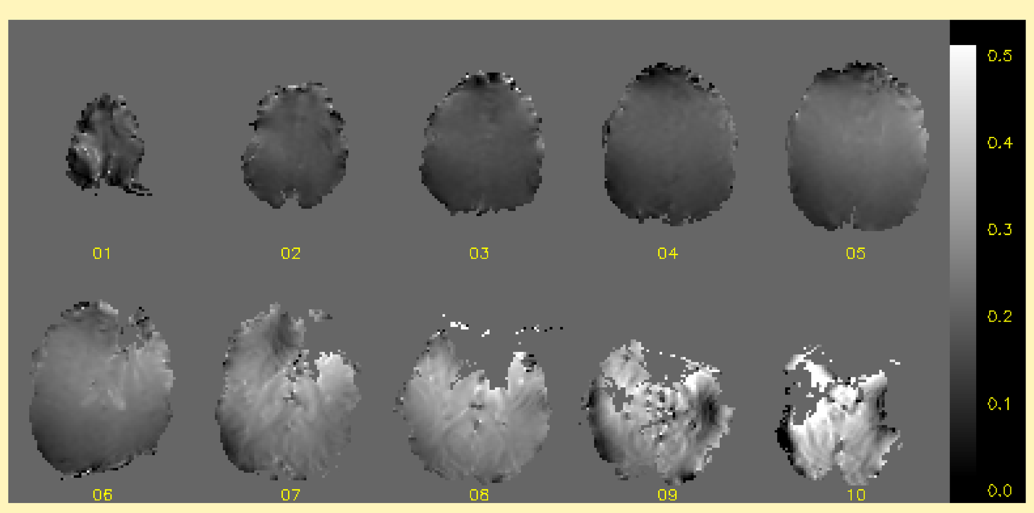

Figure 3. Amplitude of phase fluctuations correlated with the chest position, scale is in rad.; acquired with EPI at TE 30ms, TR 1s .

Solution

Hardware

In order to change the shim currents in real time independent of the scanner operation a couple of additions and modifications was required. In the gradient amplifiers an extra loop through the output sensing transformer provided a path to add a small current for the linear shim terms, driven by three current sources. These sources and the existing second input to the higher order shim amplifiers were driven by 8 DACs controlled through a 24 bit parallel port on a PCI card in an Linux PC. A serial link allowed for adjustment of the frequency of the phase continuous reference synthesizer which serves as local oscillator for the down converters in order to adjust the center frequency. The signal from the bellows was available at a serial port on the scanner, at a 4ms sampling interval.

Processing

The method consists of three separate steps: 1) calibration of the shim currents (required only once), 2) acquisition of a training data set to measure the phase changes as function of respiration (acquired at the start of every scan session), 3) the continuous compensation during normal scanner operation when the respiratory signal is used to set the shim currents; see Fig 4.

Calibration and training data are both acquired with an EPI sequence, with 12 slices of 2mm thickness and 6mm spacing, TE 30ms, TR 1s, 96x72 voxels over 240x180mm FOV. Two minutes of training data are acquired. Resulting phase maps were analyzed by fitting with 3D second-order polynomial functions, producing 10 field coefficients per fit. The calibration gives the relation between the coefficients and the shim currents, which can be inverted to calculate the currents required for a desired field. The field coefficients fitted in the training set can then be used to calculate shim currents as function of respiration to compensate the observed field changes.

The respiratory signal is projected 120ms into the future during the compensation phase, using a autoregression model, to compensate for the observed delays between the measured chest position and the field changes.

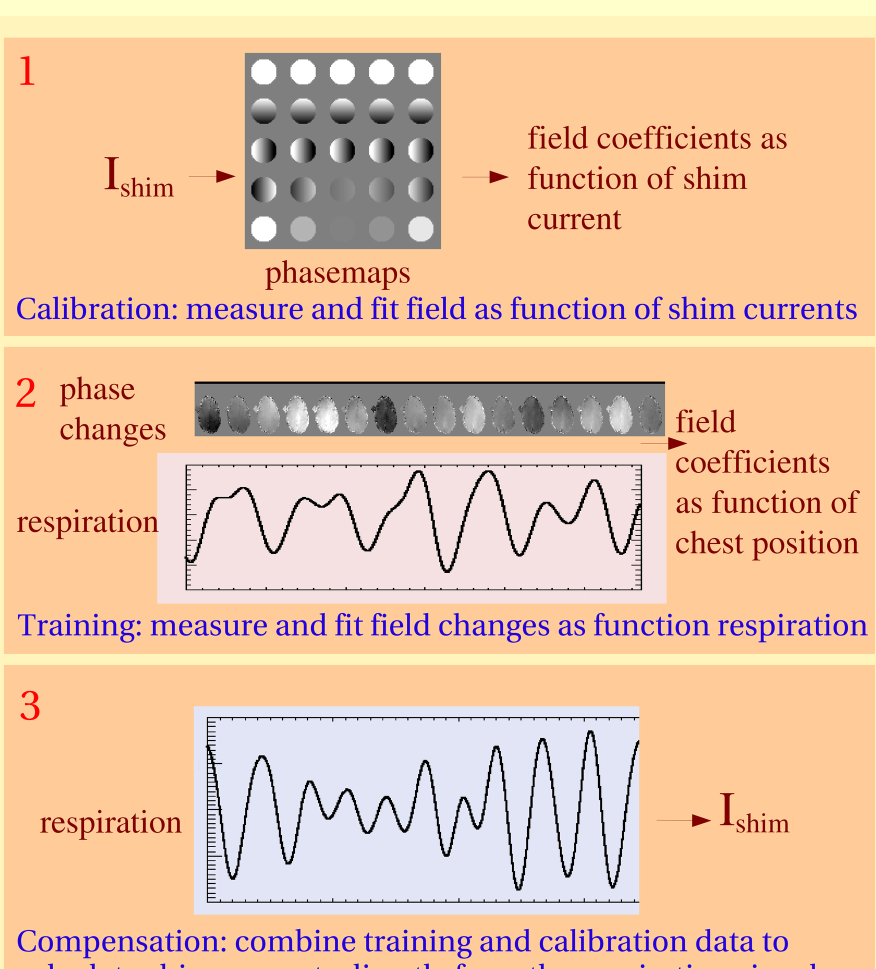

Figure 4. The three components of the RTS process.

Results

An example of the effectiveness of the correction method is shown in the Fig 2b, showing a 0.5mm resolution gradient echo acquisition. Without compensation there are several artifacts, which disappear with RTS. Fig. 5 shows a higher resolution image acquired with RTS. The improvement in phase stability in an EPI series is shown in Fig 6. Averaged over 8 subjects, the phase stability improved by a factor of 3 overall and a factor of 9 when band filtering the phase data between 0.11 and 0.49Hz (the respiratory frequency band).

By taking the EPI training data and subtracting different spatial orders of respiratory correlated phase variations, the maximum attainable stability can be estimated:

correction order	none	zero	linear	second	all
stability [Hz^2]	0.579	0.161	0.142	0.135	0.118

showing that the zero order is the most important, although each additional order does result in a significant improvement. “All” refers to a unrestricted voxel by voxel correction, which gives best achievable stability for a linear correction method and an infinite number of shim terms.

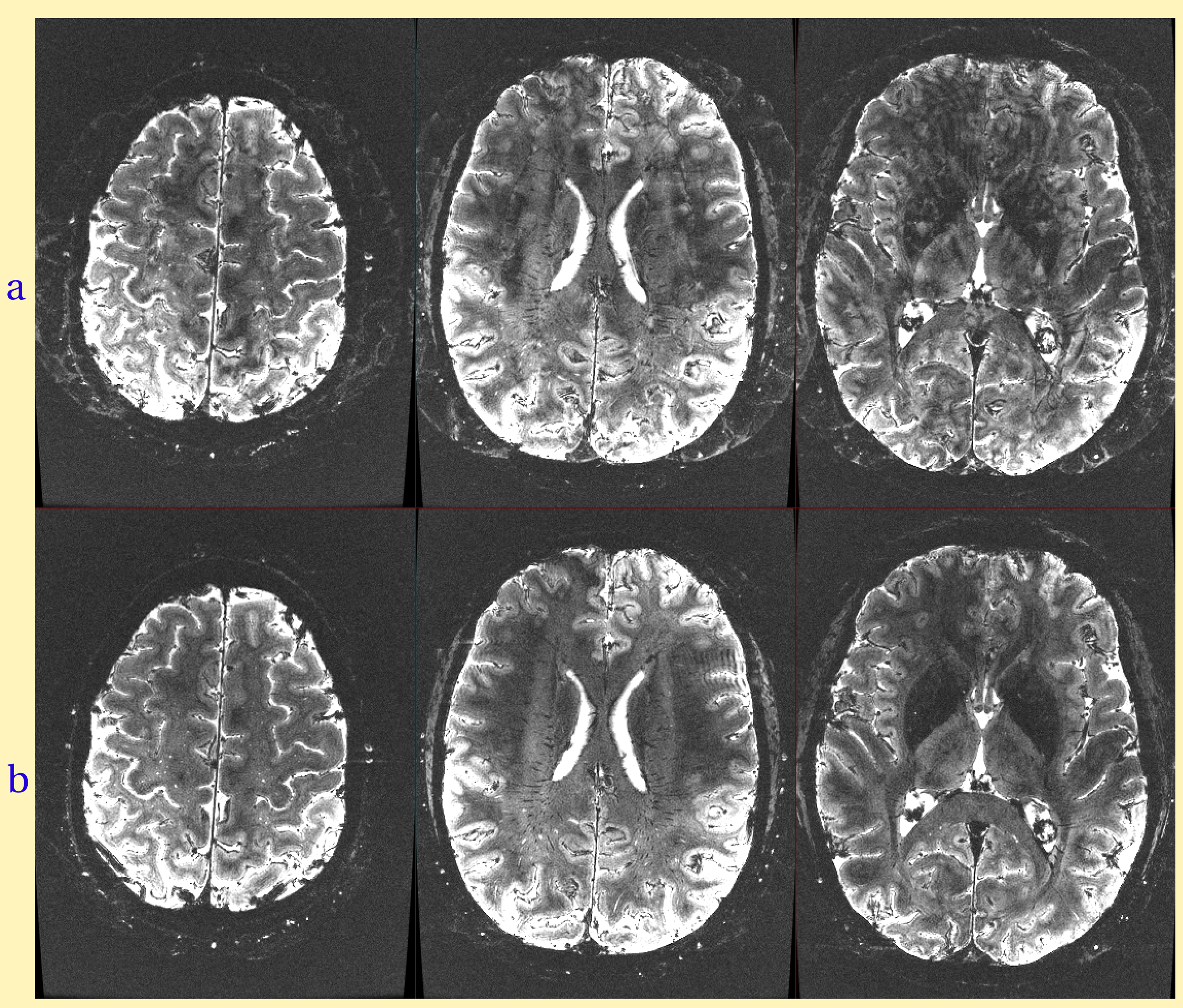

Figure 2. Gradient echo images acquired without (a) and with (b) real time shimming. Ghosting, blurring and phase interference from the ghosts are apparent in the uncorrected images. Parameters: TE 40ms, TR 500ms, 512x384 voxels/ 220x165mm, 1mm slice.

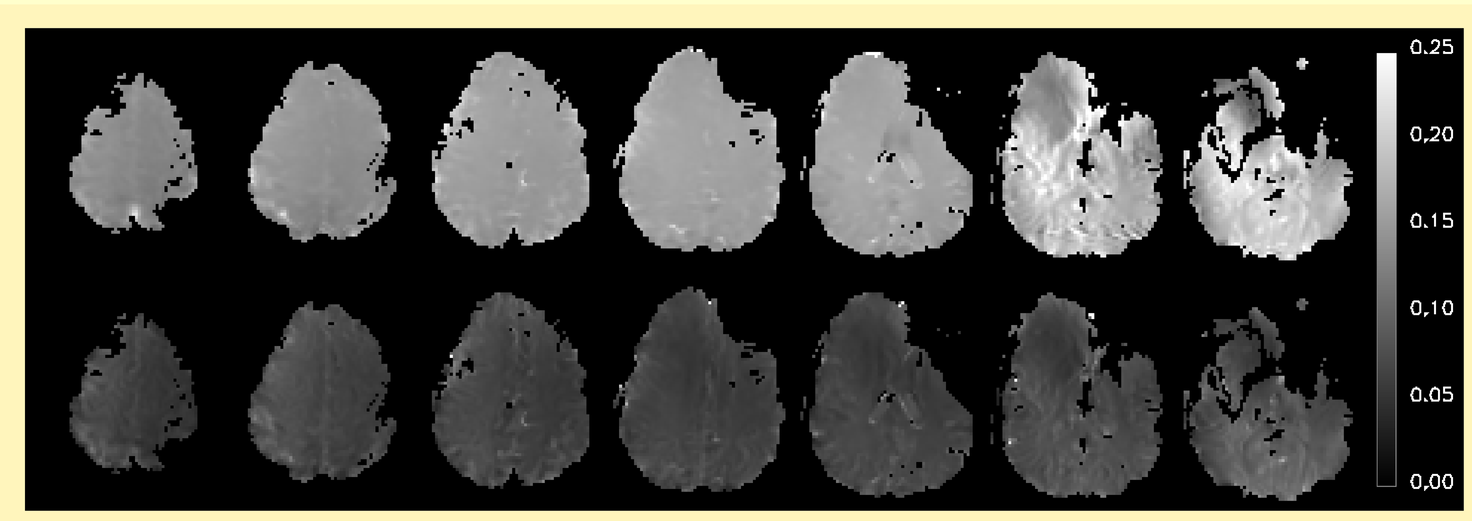

Figure 6. Phase stability of EPI data without and with RTS, the scale is in radians. The EPI was acquired with 96x72/240x180mm, 2mm slices+ 6mm gap, TE 30ms TR 1s, 120 repetitions. The phase differences over time were band filtered 0.11-0.49Hz prior to computing the standard deviation.

Conclusion

Real Time Shimming to compensate respiration related phase changes significantly improves the phase stability and image quality of all scans relying on multishot phase encoding. The method can be applied to any type of scan without the need to modify the MR sequence being used.

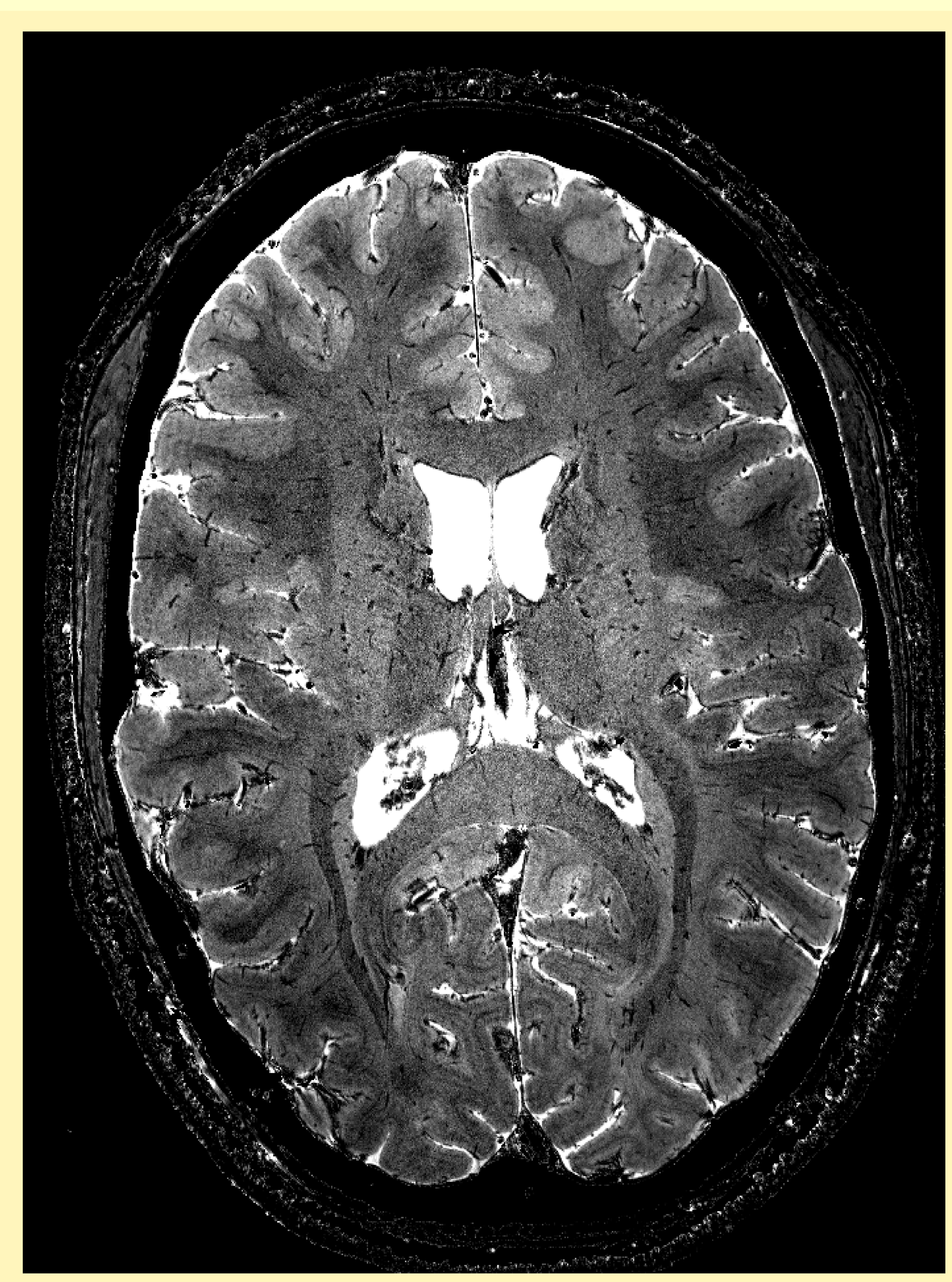

Figure 5. High resolution gradient echo image, acquired with RTS.TE 30ms, TR 500ms, 1024x768/240x180mm , 0.5mm slice thickness.

References

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