Shim Navigators for Accurate Detection of the B0 Magnetic Field Inhomogeneities Using Reference MGE Images

I. Dragonu[1], D. N. Splitthoff[1], N. Baxan[1], P. Freitag[2], J. Hennig[1], and M. Zaitsev[1]

[1]Dept. of Radiology, Medical Physics, University Medical Center Freiburg, Freibug, Baden-Wuerttemberg, Germany, [2]Bruker Biospin, Ettlingen, Baden-Wuerttemberg, Germany

Introduction: The B_0 magnetic field may change during the experiment for several reasons: physiological motion, such as breathing, subject motion and hardware imperfections, such as passive shim element heating. Changes in B_0 homogeneities can lead to unwanted signal fluctuations in EPI time course acquisitions. As suggested previously [1, 2], shim navigators may allow the detection of magnetic field evolution. It has been demonstrated [3] that the phase of a projection is not necessarily proportional to the B0 field inhomogeneities along the direction of that projection. In this work, we propose a method for detection of zero- and first-order in plane shims (f_0, A_{11} and B_{11}) based on shim navigators and reference multi gradient echo images.

Theory: The value of the projection along the x axis at time point t_0 is given by:

$$P_x(t_0) = \int C(x,y)\cdot\rho(x,y)\cdot\exp(j\cdot\varphi(x,y))\cdot\exp\left[j\cdot 2\pi\cdot TE\left(f_0(t_0)+x\cdot A_{11}(t_0)+y\cdot B_{11}(t_0)\right)\right]dy$$
$$= \exp\left[j\cdot 2\pi\cdot TE\left(f_0(t_0)+x\cdot A_{11}(t_0)\right)\right]\cdot\int C(x,y)\cdot\rho(x,y)\cdot\exp(j\cdot\varphi(x,y))\cdot\exp\left[j\cdot 2\pi\cdot TE\cdot y\cdot B_{11}(t_0)\right]dy \qquad (1)$$

where C represents the sensitivity of the receiving coil, ρ the spin density, φ the phase contributions originating from the transmit and receive coils, TE the echo time of the navigator and f_0, A_{11}, B_{11} the in-plane shims of zero- and first-order at time point t_0.

Making use of Eq. (1), one can determine the phase evolution between two navigators along the x axis acquired at two different time points t_0 and t_1.

$$\tan^{-1}\left(P_x(t_1)\cdot P_x^*(t_0)\right) = 2\pi\cdot TE\cdot\left(\Delta f_0 + x\cdot\Delta A_{11}\right) + \tan^{-1}\Big[\int C(x,y)\cdot\rho(x,y)\cdot\exp(j\cdot\varphi(x,y))\cdot\exp\left[j\cdot 2\pi\cdot TE\cdot y\cdot B_{11}(t_1)\right]dy$$
$$\left(\int C(x,y)\cdot\rho(x,y)\cdot\exp(j\cdot\varphi(x,y))\cdot\exp\left[j\cdot 2\pi\cdot TE\cdot y\cdot B_{11}(t_0)\right]dy\right)^*\Big] \qquad (2)$$

Equation (2) demonstrates that the phase of the product $P_x(t_1)\cdot Px^*(t_0)$ is not necessarily proportional to the values Δf_0 (the variation of the zero-order shim) and ΔA_{11} (the variation of the X shim). Any modification of the B_{11} value may affect the detected values of Δf_0 and ΔA_{11}. Similarly, using the projection along the y axis, any modification of the A_{11} value may influence the detected Δf_0 and ΔB_{11}. In order to resolve this influence, we acquire multi gradient-echo (MGE) images as a reference with echo times matching the echo times of the navigators along the x and y axis and having the same contrast. Since the typical TR for full coverage of the brain using single shot EPI images is much longer than the TR used when obtaining the MGE images, the flip angle of the MGE sequence should be set sufficiently low in order to avoid any T_1 contrast in the reference MGE images.

For detecting the values of Δf_0, ΔA_{11} and ΔB_{11} we use the model described by the equation (2) and the corresponding equation describing the projections along the y axis as well as the reference MGE images. A non-linear fit that minimizes the root mean squared error between the measured phase $P_x(t_1)\cdot P_x^*(t_0)$ and $P_y(t_1)\cdot P_y^*(t_0)$ was performed.

Material and Methods: All experiments were performed on a 9.4 T Bruker Biospin animal scanner (Bruker BioSpin MRI GmbH, Ettlingen, Germany) using a MGE sequence (TR = 900 ms, first TE = 1.72 ms, echo spacing = 1.11 ms, number of echoes = 12) and a modified GE-EPI sequence allowing the acquisition of four shim navigators (two shim navigators along the x axis and two shim navigators along the y axis as shown in Fig. 1). A four-channel phased-array coil was used for signal detection. Data processing of the shim navigators including Fourier transformation, phase-calculation and eventual 1-D phase unwrapping are performed in real-time on the scanner. Optionally, the navigator data can be saved for offline post-processing. Several phantom experiments were performed in order to estimate the precision of the shim navigators by varying the settings of the first-order X and Y shims in small steps. The first set of experiments was performed with a variation of A_{11}, the second set with a variation of B_{11} and the last set with a simultaneous variation of A_{11} and B_{11}. After each modification of the shim settings, EPI data with navigators were acquired. The variations Δf_0, ΔA_{11} and ΔB_{11} between time points t_1 ant t_0 (beginning of the experiment) are determined based on the shim-navigators acquired at time point t_1, the reference navigators acquired at time point t_0 (with a known shim setting) and the reference MGE images at time point t_0. For validation purposes, additional MGE images were acquired in order to measure the absolute values of f_0, A_{11} and B_{11} for each shim setting.

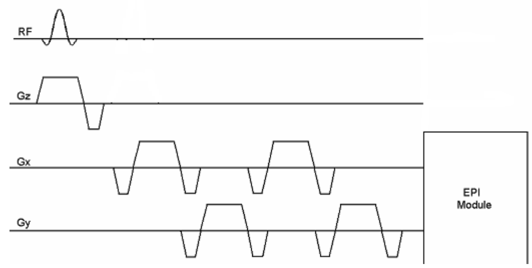

Fig. 1: Modified GE-EPI sequence allowing the acquisition of four shim-navigators along the x and y axis.

Results: Figure 2 displays the detected changes ΔA_{11}, ΔB_{11} and Δf_0 based on the four shim-navigators and the reference MGE images. These values were compared to the result of the fitting of the field maps calculated from the MGE images using all twelve acquired echoes. The results indicate that the detected shim variations using the proposed method are highly accurate. The correlation coefficient between the detected A_{11} value using the field maps and the detected A_{11} value using the shim-navigators for the first seven experiments with X shim variation was 95.79 %. The correlation coefficient between the detected B_{11} value using the field maps and the detected B_{11} value using the shim navigators for the next seven experiments with Y shim variation was 98.65 %. Even though the scanner frequency was not changed manually, we observed a frequency drift over the duration of the experiment (3 hours). The detected f_0 frequency drift using the navigators accurately matches the result obtained using the field maps.

Discussion/Conclusion: The results demonstrate that the presented method can accurately detect the modifications of the zero- and first-order field components of in plane shims. The current scanner hardware/software configuration allows real-tine re-adjustment of the zero- and first-order shim settings, based on shim navigator measurement. The current implementation of the sequence has two navigators on each axis. For higher precision of the detected values, in this work, four shim-navigators were used. Theoretically, two navigators, one along the x axis and one along the y axis, would be sufficient for detecting the variations of f_0, A_{11} and B_{11}. The acquisition of only two navigators allows shortening of the echo time of the EPI sequence which can become important at high fields. The magnetic field stability during functional MRI experiments is crucial for accurate localization of activated regions. Magnetic field variations resulting from subject breathing as well as scanner instability can cause unwanted shifts in the acquired EPI images. Consequently, the proposed method would be a valuable technique for practical applications such as fMRI or DTI.

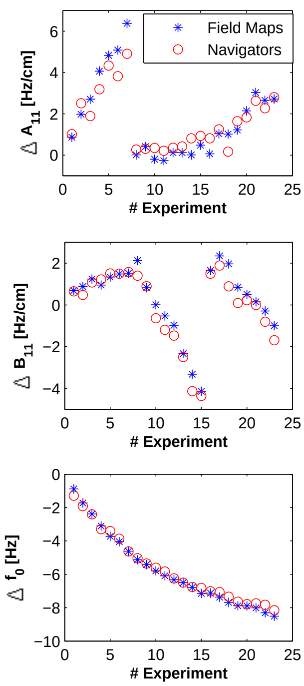

Fig. 2: Detected variations of A_{11}, B_{11} and f_0 using shim-navigators (*red circles*) and field maps (*blue stars*).

References: **[1]** Ward HA *et al*. MRM 2002; 48:771-780. **[2]** van der Kouwe *et al*. MRM 2006; 56:1019-1032. **[3]** Splitthoff DN and Zaitsev M. ISMRM 2009, Hawaii #2792

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