Placement of field probes for stabilization of breathing-induced B0-fluctuations in the brain

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Introduction B_0-fluctuations induced by breathing and body motion lead to artifacts for certain brain imaging sequences at ultra-high field (7T). A promising solution is to monitor the B_0-fluctuations during the scan using external field probes, and update the shim currents in real-time (1). It is a fundamental challenge, however, that the B_0 measurements are spatially sparse (e.g. 16 probes), and performed outside the brain. Typically, the field is modelled by a linear combination of the spatial shim fields that the scanner can produce (such as spherical harmonics up to 3rd order), and the coefficients for these spatial terms are determined by least square fitting to the field probe measurements. The probes must be placed carefully to ensure that the spherical harmonics can be distinguished using these few samples, and they must be placed close to the head so that the spatial field model is valid and to have good SNR. Here, we provide a simulation of breathing-induced B_0-fluctuations inside and around the head and use this simulated field to test different sets of probe positions. We also formulate two optimization problems to guide placement of the field probes.

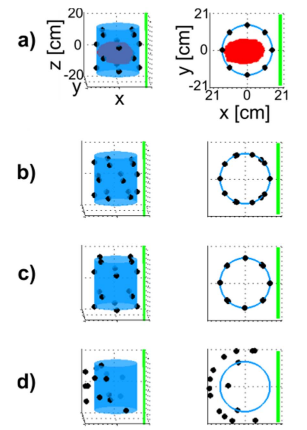

Fig 1: Sets of field probe positions tested. The markers are the field probes, the blue cylinder is the receiver coil, the green plane is the patient table and the red surface in a) is the brain mask used. The two columns show different view angles.

Methods: Field simulation of breathing-induced B_0-fluctuations was performed by acquiring an MRI scan of the upper body of a subject during an in- and an expiration breath-hold, segmenting these images into tissue and air and correcting the amount of lung tissue so it matches literature values (2) and such that the amount of tissue is preserved between in- and expiration. The air and tissue voxels were assigned susceptibility values ($\chi_{air} = 1.2566 \cdot 10^{-6}$ and $\chi_{water} = -9.05 \cdot 10^{-6}$) , and the difference susceptibility map was convolved with a magnetic dipole kernel (multiplication in *k*-space) to estimate the field distribution (3). Probe positions: A matrix **S** was computed with spherical harmonics up to 3rd order, where s_{ij} represents spherical harmonic *j*, sampled at field probe position *i*. In one optimization, the sum of squared cross-correlation terms between all columns of **S** was minimized (result in Fig. 1b). In a second optimization, columns of **S** were normalized to yield the same units for all spherical harmonics, and the condition number was minimized (result in Fig. 1c). Both optimization problems considered 16 field probes constrained to lie on a cylinder representing the receive array. Two other sets of positions were tested, the positions from reference (1), Fig. 1a, and a set of positions mostly outside the transmit coil (Fig. 1d) used in an early experiment (only 15 probes). Testing of positions was done by sampling the simulated field at the field probe positions, fitting to the spherical harmonic model, and subtracting the fitted field from the simulated field, to simulate shimming. Simulated shimming with noise: The simulated shimming was repeated 5000 times with Gaussian noise with zero mean and standard deviation 0.5Hz (1) added to the field samples at the field probe positions.

Results: Fig. 2 shows the spatial field distribution before and after simulated shimming without noise, for the different probe positions. Fig. 3 shows root mean square (RMS) values across the brain for simulations with noise. We see that probe positions a),b),c) give similar results for up to 2nd order shimming. When performing 3rd order shimming, no benefit over 2nd order is seen for positions c), while for a) 3rd order is slightly worse than 2nd order (larger spread in Fig. 3), and for b) 3rd order shimming leads to detrimental results due to bad conditioning. The positions in d) generally leads to little improvements in the field compared to the other positions.

Conclusions: We have optimized and evaluated different sets of field probe positions. Based on the simulations we recommend positions a) and c), and do not recommend full 3rd order shimming based on only 16 field probe measurements. With the optimized positions of the field probes, the spatial RMS of the B_0-fluctuations was estimated to be reduced by more than a factor of two, already with 0th order shimming.

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References: 1. Duerst Y et al. Magn. Reson. Med. 2014. 2. Molina DK et al. Am. J. Forensic Med. Pathol. 2012. 3. Salomir R et al. Concepts Magn. Reson. 2003.

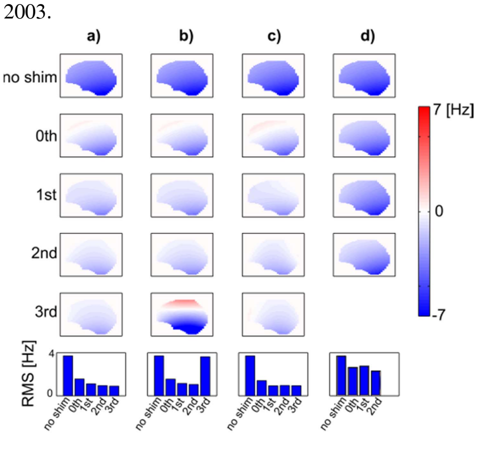

Fig. 2: a)-d) Field distribution in a sagittal brain slice with probe positions as in Fig. 1a)-d), respectively. Top row is without shimming, row 2-4 are with up to 3rd order simulated shimming. Bottom row shows RMS values over the entire brain after the different corrections. d) does not include 3rd order , as Fig. 1d) only includes 15 probes

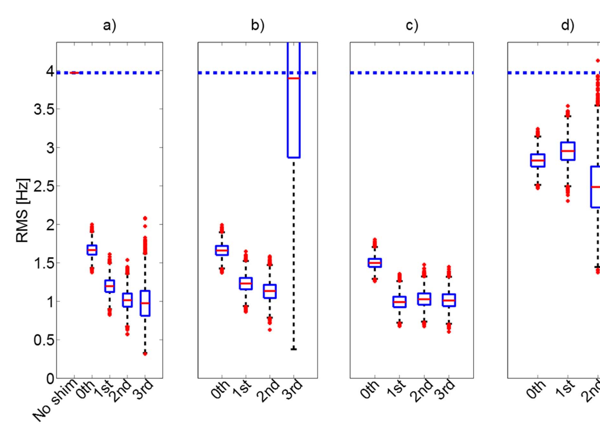

Fig 3: Results from simulated shimming with noise added. The boxplots show the distributions of RMS values across the whole brain before shimming (horizontal dotted line), and after up to 3rd order simulated shimming using the field probe positions from Fig. 1.