A shimming procedure for fMRI, optimizing the local BOLD sensitivity

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Introduction

In functional magnetic resonance imaging (fMRI), magnetic field inhomogeneities due to air-tissue susceptibility differences are well-known to lead to severe signal dropouts and geometric distortions in echo-planar images (EPI). Therefore, the optimization of the field homogeneity is an important step in the imaging process and various so-called "shimming" techniques, using linear and higher-order resistive shim coils, have been developed. The common overall goal of the many existing approaches is to calculate the corrective shim currents in order to compensate for the field inhomogeneities over a region of interest (ROI), by minimizing the spatial standard deviation of the magnetic field. However in fMRI, the BOLD (Blood Oxygen Level Dependent) sensitivity is the measure of interest, and it is only indirectly related to the spatial variation of the magnetic field. In particular, it depends on the EPI signal intensity and the local TE [1-3]. The analytical expression for an estimate of the BOLD sensitivity has been previously developed, allowing for the computation of BOLD sensitivity maps from EPI data and field maps [1-3]. In this study, a procedure has been developed that optimizes the BOLD sensitivity over a region of interest, while ensuring satisfying overall field homogeneity in order to avoid geometric distortions in the echo-planar images. The method is applied *in vivo* and compared to two other methods based on the optimization of the field homogeneity.

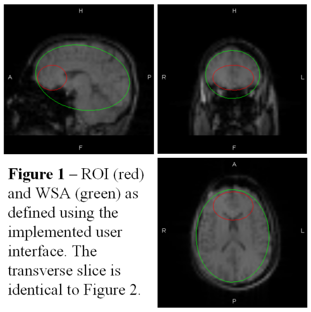


Figure 1 – ROI (red) and WSA (green) as defined using the implemented user interface. The transverse slice is identical to Figure 2.

Methods

Experiments were performed on a 3.0 T *Allegra* scanner (Siemens, Erlangen, Germany), operated with the standard head transmit-receive coil and equipped with first- (X, Y, Z) and second-order (Z^2, ZX, ZY, X^2-Y^2 and XY) shim gradients. The data were aquired on a gel phantom and on a healthy volunteer with written informed consent. Several shimming techniques were investigated and compared. The first technique is the standard manufacturer's procedure, referred to as the "3Dshim" procedure, and making use of 3D field maps to measure the magnetic field distribution. The behaviour of the 8 shim gradients is modelled using spherical harmonics, and the magnetic field standard deviation is minimized by a spatially localized fitting of the spherical harmonics onto the acquired field map. The second technique, also based on the minimization of the magnetic field standard deviation, makes use of calibrated field maps for each shim coil, as decribed by WEBB *et al.* [4] and KIM *et al.*[5]. It will be referred to as the "Calibrated Shim" or "CalShim" technique. By taking into account the shim gradient deviations from spherical harmonics, this technique allows for a more reliable prediction of the resulting field homogeneity. Calibrated field maps were also used for the BOLD sensitivity (BS) based ("BSShim") procedure. As described in detail by DEICHMANN *et al.* [1,2], the theoretical BS is proportional to the local TE and to the image intensity ($BS \propto TE \cdot I$) and is related to the field gradients by a non-linear expression. BS optimization is no longer a linear problem, and an iterative conjugate gradient technique is applied. Moreover, shim gradients opposing the phase-encoding gradient G_y lead to an increase of the local TE and the BS [2], and the optimization of the BS is expected to lead to a high contribution from G_y. Therefore, the BS optimization requires further regularization in order to avoid excessive geometric distortions due to the G_y contribution. The regularization was ensured by optimizing the BS over a given region of interest (ROI), while constraining the field homogeneity and especially the G_y component in the brain areas that are considered to be generally well shimmed (referred to as the "well shimmed area" or WSA). The first step of the constrained BSShim procedure consists in optimizing the field homogeneity over the WSA, excluding the ROI, by using the second procedure mentioned above. Then the BS is optimized over the ROI, while ensuring an increase of the magnetic field standard deviation over the (WSA $\cup$ ROI) not greater than 20% and a mean G_y not greater than 2.5 Hz/Pixel. The latter constraint limits the geometric distortions in the image to a maximum compression of 5%. This constrained procedure was compared to an unconstrained one, where the BS is optimized over the ROI only.

Results and Discussion

Phantom and *in vivo* measurements confirm the theoretical expectations, illustrated here with *in vivo* data acquired on a healthy volunteer. The ROI is positioned in the orbito-frontal area, while the WSA encompasses the whole brain (Figure 1). The measured field maps, calculated BS maps, and the corresponding EPIs are displayed in Figure 2, with identical intensity scales for comparison. Estimated field maps closely matched measured ones (data not shown), ensuring reliable prediction and optimization. The standard deviation of the magnetic field, and the mean BS and G_y with their standard deviations are displayed in Figure 3 for both the ROI and the WSA. Several cases are compared: (a) 3Dshim over the whole brain, (b) unconstrained BSShim over the ROI, (c) constrained BSShim over the ROI, (d) CalShim over the ROI only and (e) CalShim over the WSA. The global field homogeneity reached using calibrated reference maps is higher than using the 3DShim spherical harmonics approximation (Fig.3a and 3e), and a slight recovery of the dropout is observed in the frontal area (Fig 2a and 2e). The unconstrained BS optimization yields high BS in the ROI, but also leads to excessive G_y contributions and high geometric distortions in the EPI data, compressing the image and increasing the ghosting in the background (Fig.2b and 3b). The constrained procedure (c) yields a slight increase of the BS compared to the CalShim procedure (e), and no geometric distortions are observed. However, the 20% constraint on the magnetic field standard deviation proved to be too strict, as the limit was reached early in the optimization, leading to a sub-optimal BS over the ROI. Optimizing the field homogeneity over the ROI only, achieves a high homogeneity in this region (Fig.3d), but leads to severe dropouts in the image, with an interesting match between the predicted BS map and the EPI intensity pattern (Fig. 2d).

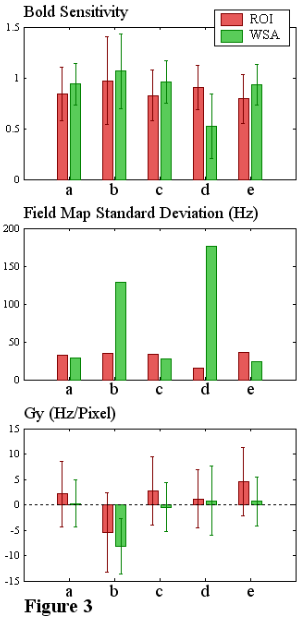
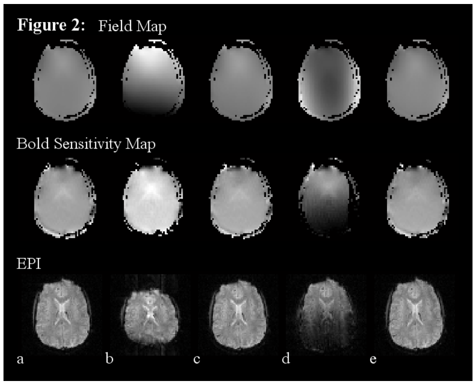


Figure 3

Figure 2:



Conclusions

This study introduces a novel way to optimize the shim in the context of fMRI. Instead of focusing on the magnetic field homogeneity, the BOLD sensitivity itself is the target of this fMRI-dedicated automated shimming procedure. Different levels of constraints still need to be investigated in order to find the most robust criteria for the BS optimization.

References: [1] DEICHMANN R. *et al.* (2002) *NeuroImage* **15**:120-135. [2] DEICHMANN R. *et al.* (2003) *NeuroImage* **19**:430-441. [3] WEISKOPF N. *et al.* (2007) *MAGMA.* **20**:39-49. [4] WEBB *et al.* (1991) *Magn Reson Med.* **20**, 113-122. [5] KIM *et al.* (2002) *Magn Reson Med.* **48**:715-722.

Acknowledgements: This work is supported by the FNRS (Belgium) and the Wellcome Trust.