A Bit of a Mouth Full: Susceptibility Artifact Reduction Using Diamagnetic Passive Shims

J. L. Wilson, M. Jenkinson, and P. Jezzard

Centre for Functional Magnetic Resonance Imaging of the Brain, University of Oxford, John Radcliffe Hospital, Oxford OX3 9DU, U.K.

Local diamagnetic passive shims can substantially reduce brain B0 inhomogeneity, resulting in greatly improved signal loss and image distortion artifacts in BOLD fMRI data. For a standard fMRI-type EPI sequence, placement of 5.5 cm^3 of diamagnetic material in the mouth reduced by 74% the number of voxels in the inferior frontal cortex experiencing >75% signal loss. A diamagnetic earplug reduced the same measure in the inferior temporal cortex by 36%. The improvement in B0 homogeneity due to a particular size and shape of diamagnetic shim can be quickly and accurately modelled, allowing the possibility of routine use within fMRI studies.

INTRODUCTION

Susceptibility artifacts hinder accurate and useful BOLD fMRI, especially at higher static magnetic (B0) field strengths. The difference in the magnetic susceptibilities of air (0.4 ppm) and tissue (- 8.9 ppm) results in deformation of the B0 field (1,2), leading to image distortion and signal loss artifacts in the rapid imaging modalities used in gradient-echo (GE) fMRI. These effects are severe in the inferior frontal cortex (IFC), superior to the sphenoid/ethmoid sinus, and the inferior temporal cortex (ITC), superior to the external auditory canal/mastoid air cells. Typically, spectroscopy, perfusion and diffusion modalities are also compromised.

Previous attempts at mitigating these artifacts include RF pulse tailoring (3), z-shimming (4), image unwarping (5) and shimming, using room temperature shim coils (6) and ferromagnetic passive shims (7). Each technique suffers from specific limitations and drawbacks. In this study, we reveal the effectiveness and practicality of utilising locally placed diamagnetic material to passively shim the IFC and ITC, indicate the accuracy of simple B0 simulations that support our results, and discuss a possible protocol for routine use of the shims within fMRI studies.

MATERIALS AND METHODS

Our diamagnetic shims were constructed from pyrolytic graphite (PG, Minteq International Inc., PA). The magnetic susceptibility of PG is anisotropic, varying from - 450 ppm (PG plane perpendicular (⊥) to B0) to - 85 ppm (PG plane parallel (||) to B0) (8). Our studies gave similar values. All data were collected on a 3 T Varian Inova spectrometer.

The "mouth shim" was constructed from PG (6 × 23 × 40 mm, PG plane within sheet), covered in thin plastic, and placed flat against the roof of the subject's mouth. It was safely held in place by a mouthpiece and supported by the subject's tongue for these preliminary studies. Axial B0 maps and GE EPIs were obtained, following an active global brain shim (6), without and with the mouth shim - no other parameters were altered. For all sequences: data matrix = 64 × 64, 25 slices and voxel size = 4 × 4 × 6 mm. For the symmetric - asymmetric spin echo B0 map: TR/ TE/ asymmetry time = 1250/ 20/ 2.5 ms. For the EPI: TR/ TE = 3000/ 30 ms, readout bandwidth = 100 kHz.

The distortion of B0 due to the mouth shim was simulated by solving Maxwell's equations using a perturbation method (2). The experimental mouth shim placement was located using a structural image. The associated simulated B0 was added to the B0 map obtained with no mouth shim to give the simulated B0 map with the mouth shim – this simple addition of B0 is valid to first order.

RESULTS

The experimental B0 maps and EPIs without and with the mouth shim are presented in Figure 1. Results refer to the IFC in the slices shown. The mean B0 offset and standard deviation (SD) were reduced by 70% and 28% respectively, through use of the mouth shim, without degrading B0 elsewhere. The simulated B0 map (not shown) was in extremely close agreement with the experimental B0 map - the mean difference over the whole brain was 0.04 ± 0.06 ppm. Substantial reductions in signal loss and image distortion artifacts in the IFC are visible in the EPIs. The number of voxels experiencing more than 75% signal loss (N^{LOSS}), after image distortion correction, decreased by 74% with the mouth shim. Signal loss modelling, using experimental B0 maps, predicted a 69% reduction.

DISCUSSION

In addition, a PG earplug (12 × 10 × 5 mm, PG plane ⊥ to B0) provides similar, but less impressive results in the ITC. On average between the two hemispheres, the mean B0 offset and SD within the ITC were reduced by 79% and 7%, respectively, without degrading B0 elsewhere, and N^{LOSS} for the ITC decreased by 36% (modelling predicted 35%).

Considering the crude shapes of PG shims used and the early stages of this investigation the improvements in B0 homogeneity in the IFC and ITC are sizeable. This study has been repeated on other subjects with successful results. Unlike some previous artifact reduction methods (3,4, 5), improvements in both signal loss and distortion artifacts are realised. In addition, relative improvements should stay constant as B0 increases.

There are safety issues in relation to the technique although none are problematic: (i) PG has a large electrical conductivity within plane introducing SAR considerations, although no effects have been observed; (ii) the shim experiences a small torque if the PG plane is neither ⊥ nor || to B0; (iii) the mouth shim can cause subject salivation and discomfort; and (iv) cleanliness of the shim must be assured. Design improvements should minimise all these problems. In particular, compartmentalisation of the PG shim would reduce induced RF eddy currents, incorporation of the PG shim within a bite bar would reduce the latter three issues, and use of a sealed disposable cover would overcome the final issue.

Placement of local diamagnetic shims inferior to the B0 inhomogeneity, in the mouth or earhole, is quick, simple and effective, in contrast to the use of local paramagnetic shims. With the ability to quickly and accurately model the B0 distortion due to a PG shim, routine use within fMRI studies is possible. For example, following a scout structural and B0 map, the location(s) of possible PG shim placement can be found, the optimal size/shape of shim(s) selected from an available set of PG shims, and the application of the shim(s) performed. We believe that the use of local diamagnetic passive shims could herald a new phase in fMRI of the inferior frontal and temporal cortices.

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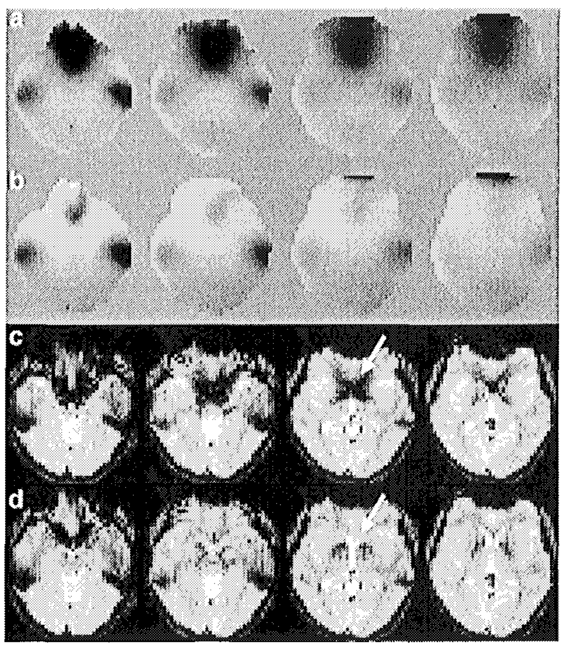

Figure 1: Brain masked axial B0 maps of the IFC are shown (a) without, and (b) with the mouth shim; range: −0.8 ppm (light) to + 0.8 ppm (dark). Corresponding GE EPIs are shown (c) without, and (d) with the mouth shim. White arrows indicate a region of susceptibility artifact reduction.