A robust automated shimming procedure for breast MR spectroscopy

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Introduction

Proton magnetic resonance spectroscopy (^{1}H-MRS) offers attractive possibilities for the non-invasive *in vivo* assessment of breast lesion biochemistry, as an aid for diagnosis [1] and an early indicator of disease response to treatment [2-4]. Effective shimming to achieve a high magnetic field homogeniety over the volume of interest (VOI) is paramount for MRS to achieve sufficient spectral resolution and avoid positional errors. This is often challenging *in vivo*, but particularly so in the breast where the off-center position of the VOI leads to an increased breakdown of the orthogonality of the shim gradients assumed when describing the spatial variation of shim fields with spherical harmonics. Furthermore, breast tumours are often marked with a radiographic tissue marker or "clip" consisting of a small metallic wire bent into a particular shape visible on X-ray mammography. This produces strong field distortions in the immediate vicinity of the marker. Strategies for shimming the breast have been described and investigated by MARIL et al. [5], combining shimming and spatial saturation pulses. However, the authors do not develop strategies for the calculation of the shim currents. To our knowledge, no adequate automated shimming procedure for breast MRS has been described so far. In this study, the regularized automated procedure described by KIM *et al.* [6] for shimming of the brain has been implemented and adapted, and is tested under breast MRS conditions. Results were compared to the manual adjustment of the linear X, Y and Z shims and to the manufacturer's automated shimming procedure which makes use of spherical harmonics to model the effect of the shim gradients.

Methods

The regularized shimming procedure described by KIM *et al.* [6] was implemented on a 1.5 T *Avanto* MRI system (Siemens, Erlangen, Germany). This method has proven to be efficient for shimming in the brain and relies on the use of calibrated reference field maps that account for the discrepancies between spherical harmonics and the actual magnetic fields produced by the shim coils, ensuring more reliable predictions. Three first-order (X, Y, Z) and five second-order (Z^2, ZX, ZY, X^2-Y^2, XY) shims are available on the *Avanto* system, with maximum amplitudes of ±5 mT/m for the linear terms, and from ±295.94 to ±727.85 μT/m² for the second-order terms. The regularization method avoids excessive shim currents, although this may be at a cost of reduced improvement of the field homogeneity, due to the inherent low power available for the second-order shims. To avoid this, the algorithm was modified, and the regularization was replaced by a simple hardware constraint, setting the exceeding shim currents to their maximum value and repeating the shimming procedure with the remaining shims. The original and modified "KIM *et al.*" procedures are subsequently referred to as the "regularized" and "constrained" calibrated shim techniques respectively. All work was performed using the Siemens breast matrix coil. Field maps were acquired with a standard gradient-echo sequence using two TE values of 4.76 and 9.52 ms respectively. Other acquisition parameters were TR = 929 ms, FoV = 150 mm, 64x64 matrix, 70 slices, 2 mm slice thickness, covering the whole breast with a spatial resolution of 2x2x2 mm³. Calibrated field maps were acquired on a 2 litre water phantom doped with 1.25g NiSO4*6 H2O + 5g NaCl. To assess the relative robustness of the different techniques to the presence of a nearby breast clip, initial work was performed using an MReye (Cook, Bjaeverskov, Denmark) breast lesion marker (outer diameter = 5 mm) suspended in a 5% gelatine phantom doped with 0.08 mM Gd-DTPA. Three different volumes of interest were assessed in the vicinity of the breast marker (Figure 1). MRS data were acquired with a point resolved spectroscopic (PRESS) sequence using the following parameters: TR/TE = 1500/30 ms, NEX = 16, 1024 data points, spectral bandwidth = 1000 Hz, VOI = 20x20x20 mm³, no water or fat suppression. The full width at half maximum (FWHM) of the water peak (4.7 ppm) was measured using the AMARES [7] algorithm in jMRUI [8]. MRS data were acquired under a number of shim settings: the default shim settings (tune up), the manufacturer's automated shimming procedure (3D shim), manual shimming using the linear X, Y, Z shims, and the regularized and constrained shim techniques. The constrained shim method was compared with the 3D shim *in vivo*, positioning the VOI in the middle of the left breast of a healthy volunteer (VOI position = (70,-60,-10) mm). All procedures were approved by the local research ethics committee, and the subject provided informed consent.

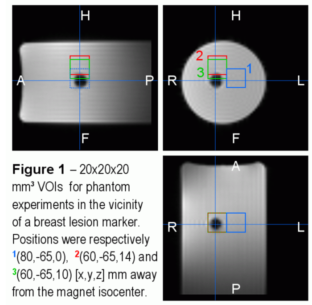
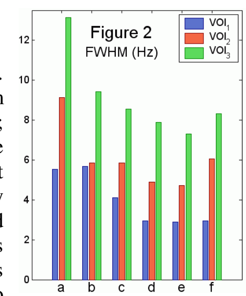


Figure 1 – 20x20x20 mm³ VOIs for phantom experiments in the vicinity of a breast lesion marker. Positions were respectively [1](80,-65,0), [2](60,-65,14) and [3](60,-65,10) [x,y,z] mm away from the magnet isocenter.

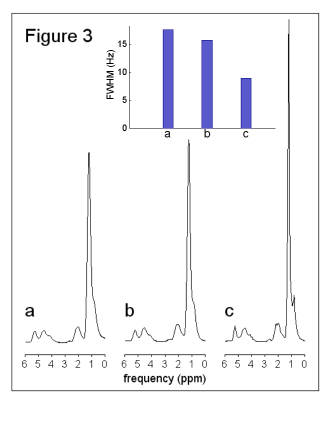
Results and discussion

The presence of the marker leads to a complete signal dropout in the gradient-echo magnitude image, as demonstrated in Figure 1. The *in vitro* FWHM of the water peak from each shimming procedure is displayed in Figure 2: tune up values (a), manufacturer's 3D shim (b), manual adjustment (c) starting from the tune up values (VOI_1) or the 3D shim values ($VOI_{2\&3}$) depending on the best starting point; constrained calibrated shim (d), constrained calibrated shim followed by a manual adjustment (e), and regularized calibrated shim (f). The magnetic field homogeneity decreased as the VOI was positioned closer to the breast marker. The 3D Shim procedure (Fig.2b) does not improve the field homogeneity for every VOI, and performs less effectively than the constrained calibrated technique (Fig.2d), probably due to the discrepancies between the actual shim gradients and the ideal spherical harmonics model in this off-center area. Our constrained technique gave the best field homogeneity in all cases. As expected theoretically, this adapted procedure, constraining the shim currents when exceeding the hardware limits, better utilizes the low shim currents available for the second-order shims, and therefore performs better than the regularized technique (Fig.2f). For VOI_1 both the constrained and calibrated procedures led to equal results as no regularization was required for this VOI position. After our constrained procedure was applied, further manual adjustment of the linear shims did not significantly improve the spectral resolution (Fig. 2e), indicating that the constrained calibrated method is robust and near-optimal. The constrained calibrated technique offered similar improvements over the 3D shim procedure *in vivo* as shown in Figure 3, which displays the spectra and the FWHM of the lipid peak (1.3 ppm) with (a) tune up values, (b) 3D shim, and (c) constrained calibrated technique.



Conclusions

In this study, the shimming procedure described by KIM *et al.* [6] was implemented and the regularization algorithm has been tested for optimal and automated shimming of the breast. Due to the calibration of the shim gradients, the technique has proven to be more reliable in predicting and optimizing the field homogeneity than the automated procedure based on the spherical harmonics approximation. The regularization algorithm was replaced by a simple hardware constraint in order to avoid excessive shim currents while taking advantage of the full power of the shim gradients. Our constrained calibrated shimming procedure consistently provided a more homogeneous magnetic field than the other shimming methods both *in vitro* for off-center VOIs at various distances from a breast marker, and *in vivo* when tested in the breast of a healthy volunteer. The constrained calibrated shimming procedure is a robust automatic shimming routine, and a promising technique for breast MRS.



References: [1] KATZ-BRULL R *et al.* (2002) *J Natl Cancer Inst.* 94:1197–203. [2] MEISAMY S *et al.* (2004) *Radiology*. 233:424–31. [3] TSE GM *et al.* (2007) *Breast Cancer Res Treat.* 104:249–55. [4] HADDADIN IS *et al.* (2007) *NMR in Biomed.* [Epub ahead of print]. [5] MARIL N *et al.* (2005) *Magn Reson Med.* 54:1139–45. [6] KIM D *et al.* (2002) *Magn Reson Med.* 48:715-22. [7] VANHAMME L *et al.* (1997) *J Magn Reson.* 129:35–43. [8] NARESSI A *et al.* (2001) *MAGMA.* 12:141–152.