ECG-triggered FASTERMAP Shimming Allows for Reproducible Shim Convergence in Spinal Cord Spectroscopy

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Introduction

Magnetic resonance spectroscopy (MRS) provides information about the biochemical processes of neuronal tissue which is complementary to conventional MRI investigations. Therefore it is a valuable tool for differential diagnostics of various neuropathologies. However, due to technical challenges it has been rarely applied to the spinal cord. Strong susceptibility changes around the spinal cord in conjunction with pulsatile flow of the cerebrospinal fluid (CSF) introduced by cardiac motion along with respiratory and spinal cord motion result in distinct B_0 field distortions. Improving the B_0 homogeneity is one of the main challenges that has to be tackled to obtain good spectral quality in spinal cord spectroscopy. Therefore applying proper shimming procedures in a clinically relevant timeframe is essential. ***In this work***, ECG-triggered FASTERMAP shimming is introduced and compared to conventional FASTERMAP shimming and shimming based on ECG-triggered B_0 field mapping. Potential and reproducibility of these techniques to improve the B_0 homogeneity respectively the line width of the unsuppressed water peak was evaluated by ^{1}H MRS at the C3/C4 level of the spinal cord in 8 healthy volunteers.

Materials and Methods: All MR experiments were performed on a Philips Achieva 3T scanner (Philips Healthcare, Best, The Netherlands) using the integrated body-coil (maximum B_1=13.5 µT) for transmission and a Philips 6-element array spine coil for reception. The pre-implemented accelerated projection-based automatic shimming routine (FASTERMAP [1]) was extended to enable ECG-triggering during acquisition of the B_0 field projections. Both conventional FASTERMAP-shimming and ECG-triggered FASTERMAP shimming were compared to shimming based on high-resolution, ECG-triggered static magnetic field B_0-mapping as described in detail previously [2, 3]. The performance of these three shimming methods was investigated including (1) only first order shim terms and (2) all first and second order shim terms. The following adjustments of the **FASTERMAP** method were identical for the non-triggered and ECG-triggered version: number of projections = 9, projection length = 500 mm, thickness = 10 mm, TR = 2 s, TE = 60 ms. Measuring of the projections and calculating the shim values takes around 20 seconds. **B_0-mapping based shimming:** B_0-maps were recorded in coronal direction with a resolution of 2.1 mm in all directions. 8 slices were acquired and a difference in TE of 2.3 ms were used for acquisition of the two necessary phase maps. The measurement time for the B_0–maps was about 12 minutes depending on the heart rate. The optimization to calculate the shim values is based on a constraint Levenberg-Marquardt least-square minimization routine and uses only the voxels included in the shim box. **ECG-triggering:** ECG-triggered acquisition is used to correct for the pulsatile CSF-flow introduced by cardiac motion via pulsatile blood in-flow into the cranium. Therefore the same trigger delay of 742 ms starting the R-wave of the ECG (after the end of the systole) was used for ECG-triggered FASTERMAP, ECG-triggered B0-mapping and ECG-triggered spectroscopy acquisitions (Figure 1). For **performance and reproducibility** tests of the described shim methods a spectroscopic voxel (approximately 2 ml volume) was positioned at C3/C4 surrounded by the shim volume with a size around 15 ml as shown in Figure 2. The position of the spectroscopic voxel and the shim box were maintained throughout all comparative measurements in each volunteer. The order of the different shim measurements was randomized and after each shim measurement the volunteer position was checked by acquiring transversal T2-weighted images. The F_0 frequency was held constant in all image scans to enable precise co-registration. If the patient position changed more than 1mm the measurement was excluded and repeated if possible. After the approval from the local ethics committee 11 adult volunteers were enrolled in the study. After excluding bulk motion impaired measurements, complete data sets of 4 female and 4 male volunteers could be finally incorporated in the study. The shim quality of the different measurements was quantified by determining the line width (full-width at half-maximum peak height (FWHM)) of the unsuppressed water signal using ECG-triggered PRESS localization (16 averages, TE = 36 ms, TR = 2 heart beats). Six highly selective, broadband outer volume suppression pulses with polynomial-phase response (PPR) [3, 4] around the spectroscopic voxel were used to reduce spurious signals of the surrounding CSF. The Mann-Whitney-U test was used to identify significant differences ($p<0.05$).

Results and Discussion: The box plots in Figure 3 indicate median (med), lower quartile (LQ) and the upper quartile (UQ) of the determined water line width for the investigated shim methods. It can be seen, that the median of the second order ECG-triggered FASTERMAP with median of 9Hz (LQ=9Hz, UQ=1.5Hz) is the lowest value which is significantly lower compared to first order FASTERMAP (med=11.5 Hz, LQ=10.2 Hz, UQ=16.5 Hz), first order ECG-triggered FASTERMAP (med=12.5 Hz, LQ=11.2 Hz, UQ=14.5 Hz) and to second order B0-Map based Shimming (med=15 Hz, LQ=9.8 Hz, UQ=25.5 Hz). No significant difference could be found comparing second order ECG-triggered FASTERMAP and second order *FASTERMAP (med=9.5 Hz, LQ=8.2 Hz, UQ=14.2 Hz) and* first order *ECG triggered B_0-Map based Shimming (med*=11.5 Hz, LQ=8.2 Hz, UQ=17.5 Hz). The reason of the observed high variance in shim convergence when using cardiac-triggered B_0-mapping based shimming is most likely due to patient motion during the long measurement time, which is needed to acquire a high-resolution 3D B_0-map. Utilizing customized arbitrarily shaped shim regions, which is one advantage of B_0-map based shimming, instead of a cuboid shim box may improve the shim quality as well as bulk motion correction. **In conclusion,** the use of ECG-triggered FASTERMAP seems to be the most robust and applicable method for clinical spinal cord spectroscopy. It is significantly faster than ECG-triggered B0 mapping and in contrast to the conventional FASTERMAP shimming artifacts due to pulsatile CSF flow introduced by cardiac motion may have less influence.

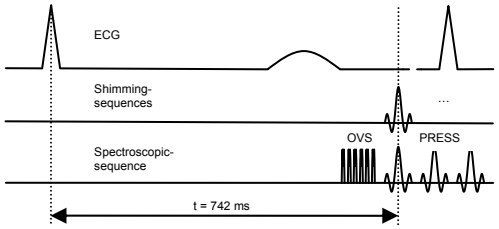

Figure 1: *Timing of the ECG-triggered FASTER-MAP, ECG-triggered B0-mapping and ECG-triggered spectroscopy acquisitions with a delay of 742 ms.*

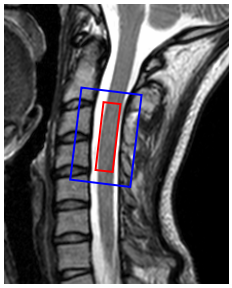

Figure 2: *Placement of the spectroscopic voxel and the shim box at C3/C4*

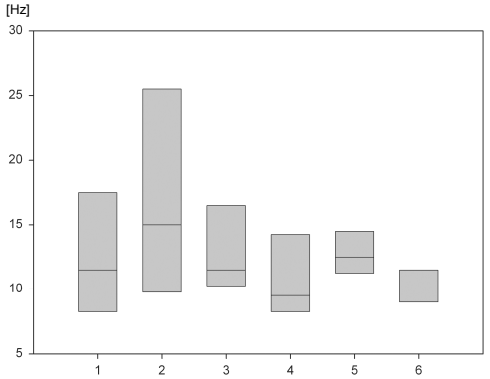

Figure 3: *Box plots of the result with median (solid line), lower quartile and upper quartile (Box) FWHM values of the unsuppressed water peak on the y axis and the six shim methods on the x axis: 1st (1) and 2nd (2) order ECG triggered B_0-Map based Shimming.1st order FASTERMAP (3), 2nd order FASTERMAP (4), 1st order ECG-triggered FASTERMAP (5), 2nd order ECG-triggered FASTERMAP (6). Note that the median of 2nd order ECG-triggered FASTERMAP (6) is 9 Hz on the lower bottom of the box at 9 Hz.*

[1] Shen J, et al., Magn Reson Med 1997;38:834–839.
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[3] Henning et al., Magn Reson Med 2008;59(6):1250-8.
[4] Schulte RF, et al., J Magn Reson 2007;186:167-175.