Evaluation of cerebrospinal fluid suppression techniques in sodium MRI at 3T

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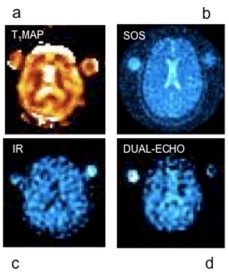

Background Sodium magnetic resonance imaging (MRI) in the brain has recently been developed for its use in the diagnosis and prognosis of a number of neurodegenerative diseases, including multiple sclerosis (MS). ^{23}Na in CSF has a mono-exponential T_2 decay (T_2=55ms) and dominates image contrast owing to its high concentration (>100mM) compared to tissue (20-40mM). Intracellular ^{23}Na in contrast exhibits a bi-exponential behaviour, with both long and ultra-short T_2 components (T_{2long}~15ms, T_{2short}~0.2-3ms)[1]. ^{23}Na-MRI, particularly at 3T, has intrinsically low SNR in comparison to traditional ^{1}H images. Voxels on the order of 4mm^3 are used to get adequate signal at reasonable scan times. Partial volume effects together with the high intensity of the CSF signal may lead to inaccuracies in the determination of ^{23}Na concentrations in peri-ventricular regions (Peri-V), a common site for MS lesions. Hence with this in mind we proposed two methods of suppressing the CSF signal to enable a more accurate quantification of total ^{23}Na in tissue: 1) an inversion recovery (IR) sequence to eliminate CSF based on exploiting T_1 relaxation differences between CSF and tissue; 2) a dual echo sequence exploiting the difference in T_2 relaxation. These methods were compared in terms of residual CSF signal and the resultant effect of CSF contamination in Peri-V regions was assessed.

MR protocols

MRI protocols were run on a 3T Achieva TX System (Philips Healthcare, Best). Axial T_2-weighted ^{1}H (PDw) scans of the brain were acquired using the Q-body coil (in plane reolution1x1mm^2). A fixed tuned volume coil (Rapid, Germany) was used for all ^{23}Na imaging and data was acquired using a UTE sequence with a 2D-radial (stack of stars –SOS)) k-space trajectory. 4% sodium agar phantoms (33mM and 66mM) were placed on either side of the head for quantification.

T1-quantification- T1 was established by running a SOS sequence with an array of inversion recovery times (TI= 10, 20, 30, 40 and 55ms). The inversion pulse was a 180° block pulse design with a duration of 0.69ms. Other sequence parameters were: TE of 0.31ms, TR=120ms, n=2 averages, acquisition bandwidth=90Hz/pixel. The field of view employed was 220x220mm^2, with an acquisition matrix of 22x22 (reconstructed to 96x96) with a nominal voxel size of 10x10x10mm^3 (reconstructed to 2.3x2.3x10mm^3), to allow reasonable scan times *in vivo*. Thirty-two slices were collected, covering the whole brain. A non-linear least squares fit routine in Matlab was used to calculate a T_1 map from the acquired data. ROI's were placed bilaterally in frontal white and grey matter (WM and GM) and in 2 regions of ventricular CSF to find the respective T_1 relaxation times.

IR protocol- After finding the T_1 value for CSF, TI was calculated to enable its effective elimination (TI=32.6ms). An inversion recovery SOS (IR) protocol was run at a FOV of 220x220x150mm, a nominal voxel size 5.75x5,75mm^2 with 6mm slice thickness, the shortest achievable TE of 0.37ms was used and 2 averages were collected.

Dual-echo protocol- A multi-echo SOS sequence with the above geometrical dimensions was run with 250Hz/pixel bandwidth in order to allow ten echoes with short echo spacing to be sampled. The shortest TE was 0.19ms and was used as the first sampling point, followed by an echo spacing of 4.8ms, 2 averages were collected. A difference map was computed between the first echo and echo 10 (TE=43.39ms).

SOS protocol- The standard SOS protocol was also run to calculate Peri-V sodium concentration without any suppression/subtraction. The spatial resolution of the ^{23}Na scan was kept at 4x4x4mm^2 to allow direct comparison of the IR and the standard sequence. All scans were ~15mins.

Post-processing and analysis

Signal-to-Noise Ratio (SNR) measurements in CSF regions were compared for the IR and Dual-Echo sequences to determine which protocol gives the best CSF suppression. T_1 corrected total sodium concentration (TSC) maps of the brain were calculated, following standard procedures that use the phantoms as calibration references[2]. Images from the IR protocol were corrected for the effects of the inversion recovery pulse on WM. (scaling factor I= (1-2*exp$^{-TI/T1WM}$ + exp$^{-TR/T1WM}$) applied to all images on a voxel by voxel basis) before concentrations were calculated. The PDw scans were used to segment the ventricular CSF using SPM8 (thresholded to 55% probability).

Using FSL each ^{23}Na scan was then registered to the PDw image. The registration parameters were then applied to the ^{1}H ventricular masks to obtain a resampled ventricular mask for each ^{23}Na acquisition (sf.net/projects/niftyreg)[3]. A Peri-V mask was also generated by dilating the ventricle mask by 1 voxel (in ^{23}Na space) in all dimensions and subtracting the original ventricles, leaving just the Peri-V region in the resulting mask (fig 2). This Peri-V region had a <55% probability of containing CSF for both IR and SOS sequences. Each mask was used to find the mean and SD of sodium concentration in Peri-V regions for the IR and SOS sequence using FSL.

Figure 2

Results and discussion

Fig 1 (a) shows a representative T_1 map. The mean T_1 of GM, WM and CSF were calculated to be 23.9±0.9ms, 21.2±0.9ms and 46.8±1ms respectively. The agar phantoms were found to have T_1's comparable to tissue (22.5±0.2ms). Fig 1 also shows sodium-weighted images for SOS (b), IR (c) and Dual Echo (d). The nulling of ventricular CSF is clearest in the IR TSC map. The clear nulling suggests that the TI used does indeed correspond to the T_1 measured for CSF and hence the partial volume affecting these voxels can be neglected in this region.

The SNR measured in CSF regions using IR and Dual echo (E1-E10) is shown in Fig 2. The IR sequence provides lower SNR in the CSF region when compared to the Dual Echo ($p<0.05$). The IR sequence has the same voxel size but a shorter TE. The difference in signal due to TE can be calculated by taking the difference in the magnetization remaining after each respective TE ($S(TE)=S_o*(0.6*\exp^{-TE/T2short}+0.4*\exp^{-TE/T2long})$), using T_{2short}(WM)=2ms and T_{2long}(WM)=15ms). The IR and E1 have 88% and 94% of the original signal from WM remaining respectively. This difference does not explain the huge difference in SNR, therefore the reduction in SNR must be largely due to the effect of the IR pulse on any CSF remaining in the Peri-V region (due to partial volume) in addition to incomplete subtraction (54% of original CSF magnetisation remaining after E1-E10, longer echo times would subtract less CSF, shorter echo times would affect tissue more).

Peri-V concentrations using the IR protocol were close to those found in tissue (mean 26.4±1.7mM) and were significantly lower than SOS (55.3±6.6mM)) ($P<0.05$),. This is an indication of less CSF contamination in the voxels due to CSF suppression. Sequences running on the same voxel size as the standard sequence would need to be run to fully validate this explanation. Longer IR pulses as suggested by Beaulieu et al could also be tested as these may increase tissue SNR whilst still allowing suppression of long T_1 CSF[4]. These results demonstrate that the IR sequence gives good CSF suppression compared to the subtraction method based on T_2 weighting, and may potentially lead to more accurate results, with potentially increased sensitivity to peri-ventricular changes, which will be of particular importance in the study of periventricular WM lesions.

[1] A Lu *et al,* Proc. Intl. Soc. Mag. Reson. Med. 19 (2011) [2] Christensen JD *et al.* Magn Reson Med 1996.[3] Durselin et al, Image Vision Comput 19 (2001) [4]Beaulieu et al, Mag. Reson Med (2005) Acknowledgements: Philips Healthcare, The MS Society, CBRC. Phantoms- G D Kenny