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). Sodium MRI has a mono-exponential T2 decay (T2=55ms) and dominates image contrast owing to its high concentration (>100mM) compared to tissue (20-40mM). Intracellular Na⁺ in contrast exhibits a bi-exponential behaviour, with both long and ultra-short T1 components (T1w=15ms, T1ul=2-3ms)². Na-MRI, particularly at 3T, has intrinsically low SNR in comparison to traditional H¹ images. Voxels on the order of 4mm³ 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 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 Na⁺ in tissue: 1) an inversion recovery (IR) sequence to eliminate CSF based on exploiting T1 relaxation differences between CSF and tissue; 2) a dual echo sequence exploiting the difference in T2 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 T₁-weighted ¹H (PDW) scans of the brain were acquired using the Q-body coil (in plane resolution 1x1mm²). A fixed tuned volume coil (Rapid, Germany) was used for all ²³Na 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 (T₁ = 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=96×96pixel. The field of view employed was 220x220mm², with an acquisition matrix of 22x22 (reconstructed to 96x96) with a nominal voxel size of 10x10x10mm³ (reconstructed to 2.3x2.3x10mm³), 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 T₁ map from the acquired data. ROI's were placed bilaterally in white and grey matter (WM and GM) and in 2 regions of ventricular CSF to find the respective T₁ relaxation times.

IR protocol- After finding the T₁ value for CSF, T₁ was calculated to enable its effective elimination (T₁=32.6ms). An inversion recovery SOS (IR) protocol was run at a FOV of 220x220x155mm³, a nominal voxel size 5.75x5.75x5mm³ 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 SOS scan was kept at 4x4x4mm³ 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. T₁ corrected total sodium concentration (TSC) maps of the brain were calculated, following standard procedures that use the phantoms as calibration references. Images from the IR protocol were corrected for the effects of the inversion recovery pulse on WM. (scaling factor = 1-(1–exp(-TE/T₁IR))^n, 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 SPMB (thresholded to 55% probability).

Using FSL each ²³Na scan was then registered to the PDW image. The registration parameters were then applied to the ¹H ventricular masks to obtain a resampled ventricular mask for each ²³Na acquisition (sf.net/projects/miftyreg). A Peri-V mask was also generated by dilating the ventricle mask by 1 voxel (in ²³Na 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.

Results and discussion
Fig 1 (a) shows a representative T₁ map. The mean T₁ 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 T₁’s comparable to tissue (22.5±0.2ms). Fig 1 (b) also shows sodium-weighted images for OSO (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 T₁ 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)=S₀(0.6exp(-TE/T₁IR)+0.4exp(-TE/T₁WM)), using T₁IR(WM)=2ms and T₁IR(GM)=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±6.8mM) (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 T₁ CSF. These results demonstrate that the IR sequence gives good CSF suppression compared to the subtraction method based on T₁ weighting, and may potentially lead to more accurate results, with potentially increased sensitivity to per-ventricular changes, which will be of particular importance in the study of periventricular WM lesions.


Figure 2

Red-CSF Blue- Peri-V

Table 1

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<th>Volume 3</th>
<th>Volume 4</th>
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