FUSS- Fast Ultrashort T_2 sensitive sodium MRS of the spinal cord

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Introduction Sodium channels have been implicated in numerous pathologies affecting the spinal cord including spinal cord injury and multiple sclerosis. ^{23}Na MRI is challenging in the cord due to short T_2 relaxivities and partial volume effects. In tissue ^{23}Na T_2 relaxation is biexponential, resulting in a short T_2 component (T_{2s}~3-4ms), which constitutes 60% of the signal, and a long T_2 component (T_{2l}~20-25ms).

To achieve the short TE needed to capture these and avoid partial volume effects ^{23}Na-MR spectroscopy (MRS) has been suggested for ^{23}Na quantification in the spinal cord using a 13min MRS Image Selective In vivo spectroscopy (ISIS) protocol with cardiac triggering (Trig_HS)[1]. However, the inversion pulses of ISIS are typically long hypersecant (HS) pulses due to their superior inversion profiles. This has implications when dealing with short T_2 metabolites such as sodium, as the inversion profiles may suffer and short T_2 components may be lost. Here we present two alternative sequences to the use of Trig HS: 1) a Fast HS based pulse (FAHS) and 2) a Fast UltraShort T_2 Sensitive (FUSS) ISIS sequence which has potential to be more sensitive to short T_2 components and like FAHS is also faster than Trig HS.

Methods

Simulations: To assess the degradation in the ISIS selection scheme, the evolution of the magnetization during the ISIS pulses was simulated. The effect of two sets of pulses was determined: the default 7.3ms HS pulses and the shorter 3.7ms sinc-gauss (SG) inversion pulses. The Bloch equations were used to simulate the effect of the pulses under the short relaxivities of ^{23}Na (T_{1WM}=21.8ms, T_{2s}=3.08ms and T_{2l}=21.2ms)[2,3].

Figure 1 shows the longitudinal magnetisation (Mz) of a 5mm slice for both T_{2l} and T_{2s}. At long T_2 the SG pulse has, at its maximum, 10% more inverted signal. At the shorter T_2 this becomes even more striking with an increase in the SG inversion profile of almost 45%. At short T_2 the HS pulse exhibits increased out of slice inversion. Hence simulations show that for short T_2 the SG pulses maybe more appropriate. Due to a standard slice definition the SG pulse has a reduced slice thickness relative to HS pulses making the effective voxel much smaller, therefore this should be taken into consideration when defining voxel size.

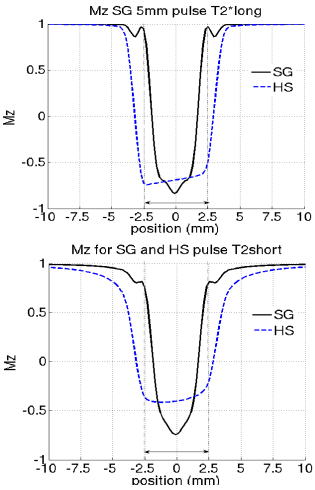

Figure 1 Simulations for a 5mm inversion for HS (--) and SG (–) pulses at long T_2 (top) and short T_2 (bottom)

In vivo MR protocol

Temporal optimization: Trig HS employed a readout of 682ms, (sweepwidth 3000Hz and 2048 samples) resulting in a minimum TR of 719ms. Such a long TR is not necessary given the short T_1 of sodium, nor a long readout given the short T_2s. By increasing the sweep width to 6000Hz and reducing the number of samples (1024) a shorter readout of 171ms was achieved. This reduced the minimum TR to 208ms. Tests on 33mM agar phantoms showed that with the same number of averages (n=800) the SNR of the spectrum was still adequate (data not shown).

Spatial optimization: A voxel size of 9x12x35mm^3 was simulated using the HS pulses, and a voxel size of 10.8x14.4x42mm^3 for SG pulses (fig 2). At the 50% bandwidth the slice thickness is similar for both sets of pulses thereby making the ISIS voxel a similar size for both pulse sets. This smaller voxel size relative to Trig HS reduces the effects of the intervertebral discs on the shimming when scanning the spinal cord with a voxel placed at C2-C3 level[4].

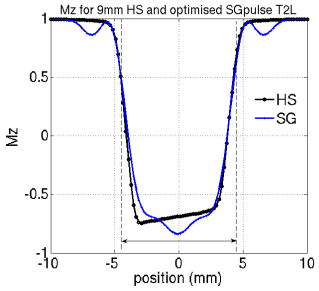

Figure 2. Simulations for a 9mm slice using the HS pulse and voxel size correction (10.8mm slice) for SG pulse

In vivo MRI comparison:

4 healthy subjects were recruited. Scanning was performed on a 3T Achieva TX system (Philips Healthcare, Best). The Q-body coil was used when imaging on the ^{1}H channel (128MHz) and a fixed tuned quadrature sodium head coil (Rapid, Germany) for transmission and reception of ^{23}Na (33.8MHz). Following a survey, ^{1}H images were taken in the sagittal and coronal planes for MRS planning. Subsequently one of two scans was run. A fast HS based scan (FAHS) using HS pulses and a voxel size of 9x12x35mm^3 or the fast ultrashort T_2 sensitive scan (FUSS) using SG pulses and a voxel size of 10.8x14.4x42mm^3 (to compensate for the slice profile). Voxels were centered on the C2-3 intervertebral disc and inner volume saturation (IVS) was used to suppress signal from CSF and bone. To avoid PNS stimulation, *in vivo* TR was increased to 300ms. These changes achieved a reduction of the scan time for ^{23}Na MRS from 13min to 4min compared to Trig HS.

Quantification: Immediately following the ^{23}Na MRS scan volunteers were removed, and replaced with an external concentration reference, on which an identical scan was run. Corrections were made for differences in T_2 between tissue and phantom ($T_{2phantom}$=44.6ms). Differences in the performance of the ISIS sequence due to differing T_1s' and T_2s' between phantom and tissue for each pulse set were also accounted for using simulations to calculate changes in inversion efficiency. The scan was then run a second time in each volunteer using the other pulse set.

Analysis: Concentrations and *in vivo* SNR were compared for FAHS and FUSS. Values obtained using Trig-HS from previous studies were also compared for each volunteer using Students t-test.

Subject	Trig HS mM	FAHS mM	FUSS mM	FAHS SNR	FUSS SNR	|ΔFAHS| mM	|ΔFUSS| mM
1	32.2	32.2	25.5	5.1	4.3	0.0	6.7
2	26.5	32.0	30.0	4.5	3.9	5.5	3.5
3	33.0	24.6	24.0	0.8	1.4	8.4	9.0
4	31.9	31.5	22.6	4.2	1.3	0.5	9.4
Mean	30.9	30.1	25.5	3.6	2.7	3.6	7.1
SD	3.0	3.7	3.2	1.9	1.6	4.1	2.7

Results Mean concentrations using FUSS were generally reduced relative to FAHS (table 1 $p>0.05$). Relative to the Trig HS protocol the mean concentrations were not significantly different although greater deviation is seen with FUSS relative to FAHS. Despite correcting for voxel volume, there was no significant difference in SNR. Mean individual differences (Δ) relative to Trig HS were doubled in FUSS although not significantly different.

Discussion Despite an expected increase in the signal using the SG pulses no improvement was seen in SNR for FUSS relative to FAHS, however this could be due to sub-optimal rest slab placement resulting in a smaller voxel, or greater sensitivity to changes in B_0 in the spinal cord. More volunteers are needed to confirm this finding. Here we have tested ISIS with shorter pulses (FUSS) against one using HS pulses. HS pulses give higher SNR and better voxel definition despite the lower sensitivity to short T_2. Values using the short 4min FAHS sequence agree well with previous scans in the spinal cord using Trig HS. These concentrations also agree with literature from brain ^{23}Na-MRI.

Conclusion Both FUSS and FAHS are an improvement relative to the previously presented Trig-HS protocol by requiring smaller voxel sizes and reducing scan time by 60%, making the sequences much more applicable in the clinic. According to simulations FUSS also has the added advantage of capturing more of the short T_2 component and hence maybe more appropriate when intracellular sodium is being scrutinized.

Ref 1) Solanky et al, Proc. 20th ISMRM, 2012 (623) 2) Solanky et al, Proc. 20th ISMRM, 2012 (1702) 3) Riemer et al, Proc. 20th ISMRM, 2012 4) Cooke et al, MRM, 2004

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