Robust large field-of-view water selective imaging at 3T with parallel transmission

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Introduction: Spectral fat suppressed or water selective imaging (e.g. using 1331 binomial pulses) for large fields-of-view is difficult to achieve, particularly at higher field because of problems in achieving a high-quality shim of the static B_0 field. Off resonance effects cause the water and fat resonances to be position dependent, causing water only selection/fat suppression to fail in some regions of the image, most frequently at the edge of the field of view. The recent development of parallel transmission (PTx) has provided greater control over the radio-frequency (B_1) field; and while this can be used to influence the homogeneity of flip angle (e.g. RF shimming [1]), we demonstrate that it can also be used to mitigate off resonance problems and so make water selective imaging more robust at 3T.

Spectral spatial pulse design can be performed in the small tip angle approximation (STA) using the method proposed in [2], generalised to include the spectral response as first discussed in [3], by extending spatial variables to include frequency. The spatial variable becomes $\boldsymbol{x} = (x,y,z,\omega)$ and 'excitation k-space' is $\boldsymbol{k}(t) = (k_x,k_y,k_z,k_\omega)$ where k_x,k_y,k_z have the usual definitions as functions of the applied field gradients, and $k_\omega(t)$ is a shifted time, $t - T$, where T is the pulse duration. The target excitation and field maps are then defined as functions of space and frequency. This formalism allows great flexibility to design RF excitations for any chosen gradient trajectory. Applying this to the case of water selective imaging, we observe that a slice or slab selective binomial water selective 1331 pulse is analogous to a "spokes" [4] pulse, consisting of four spokes all at $(k_x,k_y)=0$. These spokes trace out a set of parallel oblique lines in (k_z, k_ω), which assuming that the sub-pulse duration is small compared to the gap between sub-pulses, can be approximated as a set of spokes along k_z separated in k_ω. If we now focus on performance within the slice we can neglect z, so that the excitation k-space trajectory consists of four points, all at $(k_x,k_y,k_z)=0$ with a different k_ω (the times of the centres of the sub-pulses). Optimisation of a 4-pulse "binomial" sequence then amounts to solving for the complex weightings to be applied to each sub-pulse, for each coil. This is a significantly smaller problem to solve than optimising for the entire RF pulse, making it computationally fast, so potentially suitable for real time application.

Methods: The problem was formulated in two spatial dimensions, and from -600Hz to +600Hz; it was solved using magnitude least squares optimization (MLS) [5]. Spatial locations not containing the object were masked and excluded from the calculation. The mask was extended to the frequency domain so that only bands of ±20Hz centred on 0Hz ("water band") and -400Hz ("fat band") are included in the optimisation. The target excitation was a uniform flip angle in the water band and zero in the fat band, for all spatial locations. The optimisation goal of flip angle uniformity in water can compete with quality of fat suppression; a weighting matrix was introduced (as in [2]) in order to achieve a good balance (water band had relative weight of 0.25).

All scanning has been performed using a whole-body 3T Achieva MRI system (Philips Healthcare, the Netherlands) equipped with an 8-element parallel transmission body coil [6]. The sequence has been tested on a combination of phantoms and a healthy volunteer. Slice selective B_1 maps were acquired using the Actual Flip angle Imaging method [7] with the array element mapping technique described in [8] (acquisition time 2m31s). A B_0 map was obtained using a low flip angle multi-echo gradient echo sequence with five in-phase echoes (acquisition time 26s). B_0 was estimated using a linear fit to the phase from each echo. Since the slice selection gradient is not important for the in plane behaviour of the sequence, we used non-selective pulses and a 3D gradient echo readout, so that the nature of the excitation over a larger volume could be assessed.

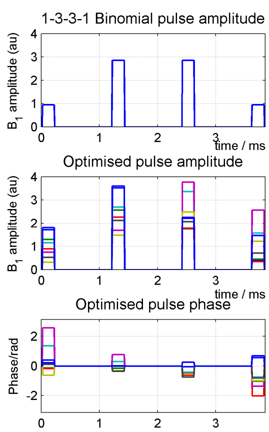

Figure 1

Results: Figure 1 shows the 1331 and optimised pulses, with the same magnitude scaling. The peak B_1 from a single channel is approximately 30% higher for the optimised pulse however the mean square of the calculated amplitudes is 10% lower for the optimised pulse; this suggests that the SAR may actually be reduced, however a detailed calculation using an E-field model would be needed to confirm this. The images in figure 2 show the slice for which the optimisation was performed. It is clear that the quality of fat suppression has been improved, especially for an anterior region where it had previously failed (see detail images). In fact the uniform fat suppression was achieved for z = ±60mm. Improved homogeneity of the water excitation band in the slice of interest was also seen; the STA model shows RMS deviation from uniformity decreased from 22% to 9%.

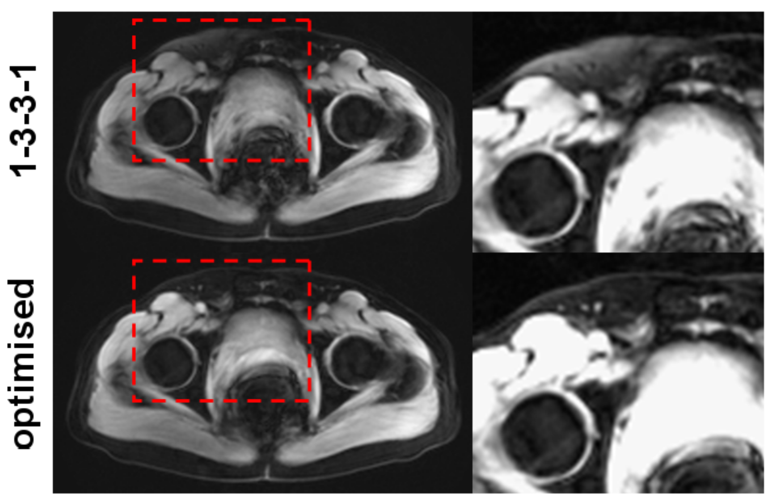

Figure 2: Whole field of view (left) and detail section indicated by red box (right) from acquired images. The windowing is the same for images in each column

Discussion & Conclusions: As is apparent from figure 1, the only modification to the sequence is the relative weighting of the pulses, making direct use of the spatial control of the B_1 field afforded by PTx, with no other changes. Solving for so few parameters has potential to be more robust with respect to poor quality calibration data; this has yet to be fully explored. The problem has been formulated in order to make maximum use of the extra degrees of freedom available. For example, restricting the target to narrow bands in the frequency domain allows the frequency response of the solution to be asymmetric around 0 Hz - this is possible because spatially resolved B_0 information is included in the calculation. Further spatial control could be introduced by adding gradients on the x and y axes in order to offset the spokes in k_x and k_y, and this may be useful particularly where the coil geometry is less favorable. In summary, finer control of the B_1 fields has been shown to improve spectrally selective excitation performance (in both pass and stop bands) over a large field of view, suggesting that PTx has the potential to play a significant role in this kind of application.

References: [1] Ibrahim et al, MRI 2001:19; [2] Grissom et al, MRM 2006:56; [3] Morrell et al, MRM 1997:37; [4] Saekho et al, MRM 2006:55; [5] Kassakian, UCB PhD Thesis 2006; [6] Vernickel et al, MRM 2007:58; [7] Yarnykh, MRM 2007:57; [8] Nehrke et al, ISMRM'08 #353