Experimental demonstration of diffusion signal enhancement in 2D DESIRE images

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Introduction Higher magnetic fields and gradient strengths bring the full implementation of the DESIRE (Diffusion Enhancement of SIgnal and REsolution) technique[1,2] within reach. As opposed to standard diffusion-weighted sequences, this method gains signal through diffusion. It measures the overall volume of saturated spins resulting from a localized saturation pulse applied for a given amount of time. The higher the diffusion coefficient at that location, the larger the number of spins effectively saturated and thus the higher the signal. Each voxel in a DESIRE image is therefore the difference between overall signal in the selected image volume, with and without voxel saturation. The method has been previously successfully implemented in 1D[3,4]. Here we report on the implementation of 2D DESIRE with high spatial resolution and the evaluation of enhancement in three different media.

Materials and methods MR imaging was performed in a 17.2 T magnet (Bruker BioSpin) equipped with maximum gradients of 1 T/m and using a home-built microcoil as RF transceiver. The phantoms were cylindrical glass capillaries (500 µm ID) filled with either distilled water ($D_{water} \approx 2.4 \times 10^{-3}$ mm²/s) or silicone oils ($D_{oil1} \approx 1.8 \times 10^{-4}$ mm²/s and $D_{oil2} \approx 9 \times 10^{-6}$ mm²/s). The coil and capillary were immersed in FC-40 to improve B_0 homogeneity. Spiral-shaped k-space trajectories and RF square pulses needed for the localized saturation were generated using custom-written Matlab (The MathWorks, MA, USA) scripts. The aimed saturation was a 60 µm diameter infinite cylinder. The selected image volume was a 250 µm-thick axial slice in the phantom, in which the saturation appeared as a 60 µm "hole". The resulting localized saturations were first imaged with a standard spin-echo sequence to ensure their compliance to the theoretical pattern. DESIRE images were then produced by displacing the saturation "hole" over a 12 x 12 grid (720 x 720 µm²) in the cross-sectional plane of the phantoms and acquiring the overall FID from the slice for each hole position, as well as a baseline signal level without saturation. The signal level S was defined as the area under the peak in the Fourier transform of the refocused FID. The enhancement E in each voxel was calculated using the formula $E(x,y) = \frac{S_0 - S(x,y)}{S_0} \times \frac{V}{\varepsilon} - 1$, with S_0 the baseline signal, S(x,y) the signal after saturation of voxel located at (x,y), V the imaging slice volume and ε the direct saturation volume[2]. The total saturation time (and hence the diffusion time) was 336 ms (Figure 1), translating into diffusion distances of 28 µm, 7.8 µm and 1.7 µm in the water, oil1 (thin oil) and oil2 (thick oil) samples, respectively.

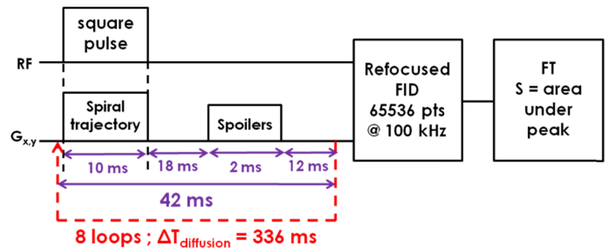

Figure 1. Timeline of DESIRE image acquisition. The sequence is repeated for each pixel in the image (i.e. each hole position), with TR=10s to allow for T_1 recovery. The hole position is determined by the RF pulse phase while the resolution (hole size) is determined by the k-space trajectory.

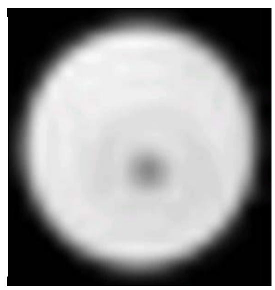

Figure 2. Spin-echo image of a 60 µm saturation hole in a 500 µm water phantom. TE=8.5ms/TR=5s /30x30x250µm³/ quadratic image smoothing.

Results and discussion The resulting saturation in water after a single loop (42 ms) is shown in Figure 2. The full width at half maximum of the effectively saturated region is 60 µm, consistent with theoretical saturation size. The first two oscillations of the sinc saturation pattern are visible but very limited, which validates the use of square pulses for this sequence. Figure 3 shows DESIRE images (enhancement maps) obtained in water, thin silicone oil and thick silicone oil. As expected, the higher the diffusion coefficient in the sample, the greater the enhancement obtained with DESIRE. In the thicker silicone oil, enhancement is close to zero (1.7µm diffusion length << 60µm hole size), but the image is very noisy due to small signal differences (S_0-S(x,y)). DESIRE images of the thinner silicone oil and of water display a variability of 16% and 15% respectively across a central 4 x 4 ROI (red squares), attributable to B_0 and B_1 inhomogeneities. The enhancement levels obtained are E_{water} = 3.0 and $E_{thin\ oil}$=1.9 (averaged over the entire slice). These enhancements are superior to the theoretical predictions[2] of $E_{th,\ water}$=1.3 and $E_{th,\ thin\ oil}$ = 0.32, calculated assuming continuous saturation and neglecting T_1 effects. The disagreement could be caused by the imperfect saturation pattern produced by square pulses and by the imperfect spoiling between pulses during the saturation train, resulting in direct saturation.

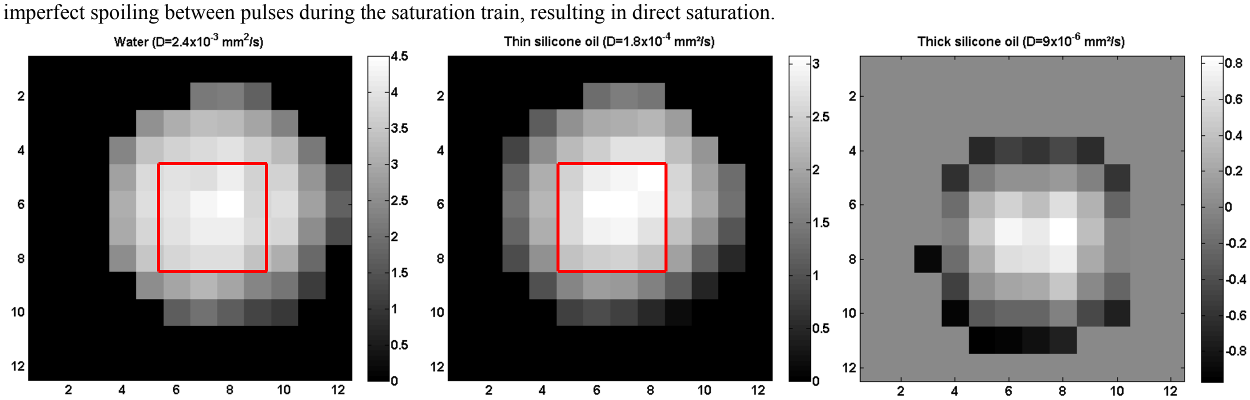

Figure 3. DESIRE images of three phantoms: water, thin silicone oil and thick silicone oil. The image resolution is given by the saturation hole size (60 µm per pixel). The phantom diameter is 500 µm. The colorbar is in units of enhancement.

Conclusion The DESIRE technique has been successfully implemented in 2D and produced diffusion weighted images with 60 µm resolution in which strong diffusion translates into larger signal. Even higher enhancement levels can be attained using more localized saturation, which would require stronger gradients, and/or by making use of parallel transmission in order to reduce the saturation hole size while keeping the pulse duration reasonably short. Imaging of multi-compartment phantoms and barriers is in progress.

References [1] P.C Lauterbur, W.B. Hyslop and H.D. Morris, in XI ISMRC, Vancouver, B.C. (1992) [2] C.H. Pennington, Concepts in Magn. Reson. Part A, 19A (2003) [3] L. Ciobanu, A.G. Webb and C.H. Pennington, JMR 170 (2004) [4] M. Weiger, Y. Zeng and M. Fey, JMR 190 (2008).
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