Enhanced Diffusion Weighting Generated by Selective Composite Adiabatic Pulses

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Introduction: Frequency selective adiabatic full passage (AFP) pulses have been used in imaging and localized spectroscopy with high tolerance to B_1 inhomogeneity [1-3]. Previous research demonstrated that selective chirp AFP pulses generate spin phase that is quadratically proportional to the local spin resonance frequency [4]. This nonlinear phase variation across the selected slice was compensated using two identical AFP pulses [1, 2, 4] to generate a robust spin-echo. Conversely, the nonlinear phase dispersion can also be increased using alternate frequency sweep (AFS) composite AFP pulse trains [5] incorporated into the localization by adiabatic selective refocusing (LASER) sequence [2] to increase diffusion weighting. However, a preliminary study using the LASER sequence demonstrated that the apparent diffusion coefficient (D) could not be measured accurately in nickel(II) doped water phantoms with short T_2, due to the small b-value produced by the selective AFP pulses alone. In the current study, a pair of pulsed gradients was incorporated into the LASER pulse sequence to increase the associated b-value. The purpose of this study was to determine whether selective adiabatic composite pulse trains could produce enhanced diffusion weighting and be used in combination with pulsed gradients to measure ^1H_2O diffusion in phantoms spanning of a wide range of T_2 values. An expression for the b-value generated by the LASER sequence was derived using the Bloch-Torrey equation following the method previously described [6]. A conventional pulsed gradient spin-echo (PGSE) sequence was employed as the gold standard for diffusion measurements in all phantoms.

Methods: Frequency selective adiabatic composite pulse trains consisting of 1, 3, 5, or 7 hyperbolic secant (HS1, R10, [2]) AFP-AFS pulses were used in the LASER sequence (Fig. 1). Pulsed gradients were added symmetrically on both sides of the refocusing selective adiabatic composite pulse train separated by a diffusion time (Δ) (Fig. 1). Six phantoms (Ph-1 to Ph-6) were studied on a 4T Varian whole body MRI with a Siemens Sonata gradient coil using a hybrid birdcage transmit/receive radio frequency coil (7.7 cm ID). Phantoms consisted of 2.8 cm diameter (50 ml) plastic tubes containing a mixture of 10 µm ORGASOL polymer beads and 2 mM Gd-DTPA dissolved in 5% agar (Ph-1), and nickel(II) ammonium sulphate hexahydrate doped (0.8 - 56.3 mM) water solutions (Ph-2 to Ph-6). The transverse relaxation time constant T_2 was measured from a single 5 mm transverse slice in each phantom using a spin-echo (SE) sequence (TE = 40 – 60 ms in steps of 5 ms). The repetition time (TR) was varied (2 - 4 s) for each phantom to minimize T_1 saturation. The diffusion coefficient (D) of each phantom was measured with both PGSE and LASER by varying G_d while fixing Δ and TE for a particular phantom (FOV = 4 cm, matrix = 64 x 64, G_d = 0 – 3.5 G/cm in step of 0.5 G/ cm, TE = 62 - 72 ms, TR = 2 – 4 s, δ = 10 ms, Δ = 35 – 40 ms, slice thickness = 5 mm). Ph-1 and Ph-4 were measured using 1, 3, 5, and 7 AFP pulses in the AFP-AFS pulse train, while other phantoms were measured with 1 and 5 AFP pulses only. T_2 time constants were calculated from the linear regression of the natural logarithm (ln) of the image signal intensity (SI) of the SE images with TE. The D-value for each phantom was calculated by the linear regression of ln(SI) (PGSE or LASER image signal intensity) with the b-value. The b-values for the PGSE and LASER sequences were calculated using Stejskal-Tanner equation [6] and self-derived equations, respectively.

Results: Typical diffusion weighted images are shown in Fig. 2. Increased image intensity was observed in the bead phantom (Ph-1) while decreased image intensity was observed in the nickel(II) doped water phantom (Ph-4) as the number of pulses in the AFP-AFS pulse train increased (while maintaining a constant TE (72 ms) and pulsed gradients (3.5 G/cm)). In the bead phantom (Ph-1), there is a clear increase in signal intensity associated with the use of more refocusing pulses in the AFP-AFS pulse train (i.e. 7 AFP line is above the 1 AFP line), while the converse is true for Ph-4. The T_2 time constants and D-coefficients measured for each phantom are summarized in Table 1.

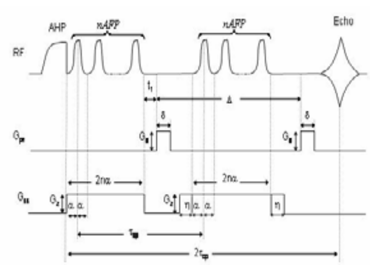

Figure 1

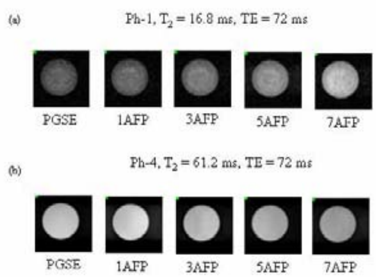

Figure 2

Table 1. The measured D-coefficients and T_2 time constants

Phantom	T_2 (ms)	PGSE	1AFP	3AFP	5AFP	7AFP
Ph-1	16.7±0.2	0.75±0.04	0.74±0.02	0.80±0.02	0.86±0.02	0.94±0.02
Ph-2	21.2±0.1	2.24±0.03	2.19±0.03		2.31±0.04	
Ph-3	43.3±0.1	2.32±0.02	2.23±0.03		2.46±0.04	
Ph-4	61.2±0.4	2.30±0.02	2.24±0.02	2.33±0.02	2.33±0.02	2.26±0.01
Ph-5	131.1±0.7	2.40±0.04	2.30±0.02		2.40±0.04	
Ph-6	555.6±3.1	2.28±0.02	2.16±0.02		2.33±0.04	

Discussion: A diffusion-weighted imaging sequence incorporating LASER was successfully implemented and used to measure the apparent diffusion coefficient in phantoms exhibiting a wide range of T_2 relaxation time constants. In comparison to the conventional PGSE sequence, the diffusion-weighted LASER sequence can generate unique diffusion contrast at the same pulsed gradient amplitude and TE due to the nonlinear phase dispersion generated and the spin-locking effect associated with the AFP-AFS pulse train. The combination of $T_{2\rho}$, T_2, and diffusion weighting produced by the AFP-AFS-LASER sequence has demonstrated opposite effects on image signal intensity depending on the sample microscopic susceptibility characteristics [7, 8]. This important feature of the AFP-AFS-LASER sequence in comparison to the conventional PGSE sequence may be used to identify the presence of magnetic perturbers that have different magnetic susceptibility compared to surrounding material (i.e. tissue).

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