New Approach for Simultaneous Measurement of ADC and T_2 from Echoes Generated via Multiple Coherence Pathways

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Introduction

The study of rotational and translational diffusion requires the measurement of both the T_2 and apparent diffusion coefficient, quantities that are typically measured in separate experiments. The exploitation of echoes generated via multiple coherence transfer pathways offers an opportunity for creating T_2 and ADC maps simultaneously from a single experiment. An RF pulse causes coherences to be transferred from one order to other orders. A series of RF pulses can therefore generate multiple echoes via different coherence pathways with each one being uniquely encoded. Here we demonstrate two possible pulse sequences, each using two coherence orders between the initial two pulses, only one of which will be attenuated by diffusion: M = 0, -1 or 0, +1. This technique is dubbed *SMART* (Simultaneous Measurement of ADC and Relaxation Time).

Materials and Methods

In order to generate the required coherence transfer pathways, an additional RF pulse is placed at the beginning of a pulsed gradient spin echo (PGSE) sequence [1] (Fig 1). This first RF pulse will rotate the magnetization so as to create three components (M_z, M^+, M^-), each representing the coherence orders M = 0, +1, -1. Notably, a gradient pulse can only impart spatial phase modulation on transverse magnetization. In the N version of the *SMART* sequence (Fig.1a), the M = -1 coherence pathway is refocused to form the N echo, but, due to diffusion, the signal is attenuated. The M = 0 coherence pathway will not be affected by the diffusion gradient in the *T* period, and is refocused to form the Z echo. The Z echo is refocused again to form the Z2 echo ($TE^{Z2} = TE_1 + TE_2$), which is used to probe T_2 decay effects. In the P version (Fig.1b), the M = +1 coherence pathway is refocused to give the P echo and, similarly, its intensity will be attenuated due to diffusion. The M = 0 coherence pathway experiences the same effect as in N.

Experiments were carried out on a 400MHz Bruker Avance™ scanner using the *SMART* N/P, CPMG, and PGSE sequences. The phantom was a 5mm NMR tube filled with 0.5mM $GdCl_3$ doped distilled H_2O. Common imaging parameters for the N/P, CPMG, and PGSE sequences were TR = 600ms STH = 1mm, NEX = 4, temperature = 21-23°C, 64×64, δ/Δ = 2/27ms, while for N sequence: θ = 69.1°, T/TE_1 = 11/12ms; G_d varied from 0-30G/cm in steps of 10G/cm; TE_2 varied from 40 to 160ms; phase cycling: φ_θ(x, y,-x,-y), φ^Z_{rec}(-x,-x,-x,-x), φ^N_{rec}(-x, y, x,-y), and φ^{Z2}_{rec}(x, x, x, x); for the P sequence: θ = 59.5°, T/TE_1 = 12/37ms; G_d varied from 0-40G/cm in steps of 10G/cm; TE_2 varied from 20 to 180ms; phase cycling, same as N except: φ^P_{rec}(-x,-y, x, y); for CPMG: echo spacing/number = 10ms/25; for PGSE: diffusion gradient varied from 0 to 40G/cm in steps of 10G/cm.

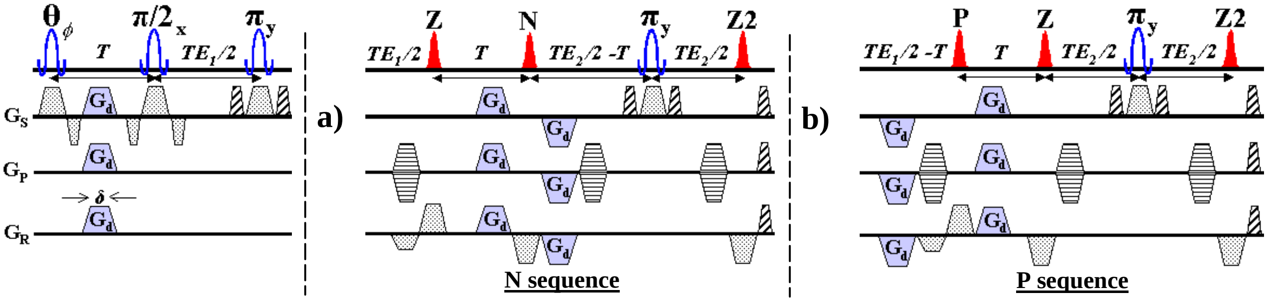

Fig. 1 *SMART* N (a) and P (b) pulse sequences (not drawn to scale). Spoiling gradients were placed around the π pulses and at the end to prevent spurious echoes.

Results and Discussion

Fig. 2a and 2b show the ADC map (G_d = 20G/cm, along G_R) and T_2 map (TE_2 = 160ms) respectively, both created with the *SMART* N sequence. T_2 and ADC (G_d along G_R) values measured from the *SMART* N and P sequences are listed in Table 1, alongside values obtained by conventional CPMG and PGSE methods. The *SMART* N/P measurements are averages of experiments in which TE_2 ranged from 60-160ms and G_d ranged from 10-40G/cm. Our results suggest that the ADC/T_2 measurements from the *SMART* N/P sequences are uncoupled. The *SMART* N/P T_2 values will naturally vary more since we averaged over a range of TE_2 values. Nevertheless, the SMART derived T_2 values were found to approach the CPMG reference value (87.6 ms) at longer TE_2 delays (84.1 and 84.7 ms for N and P, respectively, at TE_2=140 ms). One advantage of the N sequence is that TE_1 can be shorter than in P, and so N can measure smaller T_2 values. The capabilities of the *SMART* N/P sequences could be enhanced by acquiring a train of Z2 echoes, resulting in an expanded dynamic range of measurable T_2 values while minimizing inter-echo diffusion effects [2].

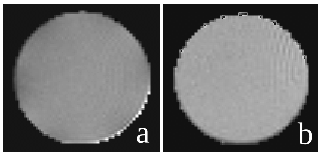

Fig 2 *SMART* N maps (a) ADC (b) T_2

Table 1. T_2 and ADC values measured with various methods

Measurement	CPMG	PGSE	SMART N	SMART P
T_2 (ms)	87.6	n/a	78.0 ± 4.5	79.1 ± 4.0
ADC (10^{-5} cm^2/s)	n/a	2.02	1.91± 0.20	1.97± 0.04

The intensities of the N, P, Z and Z2 echoes depend on the flip angle of the θ RF pulse. Fig. 3 shows the θ flip angle dependence of the *SMART* P sequence. The P, Z and Z2 signal intensities have been normalized to their respective maximum values. Note the sinθ and cosθ dependence for the P and Z/Z2 echoes, as expected. The deviation at higher flip angles is due to increased difficulties in achieving such large angles using slice-selective *sinc* pulses which can, of course, be remedied using adiabatic pulses, for example.

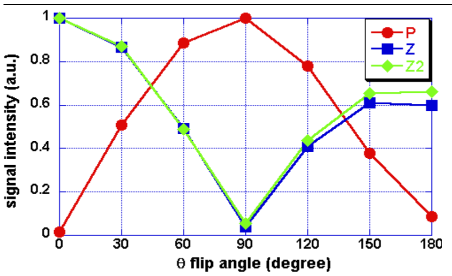

Fig 3 (left) P, Z, Z2 θ flip angle dependence

References **1.** Callaghan PT. Principles of NMR Microscopy, Oxford University Press, 1993.
2. Carr, H.Y. and Purcell, E.M. (1954). *Phys .Rev.* **94,** 630.

Conclusion

These results are the first demonstration of simultaneously, in one experiment, measuring T_2 and ADC values using the *SMART* N and P sequences. *SMART* N/P T_2 and ADC maps compare favorably with those created using conventional CMPG and PGSE methods.