Effect of distant dipolar field and T_2 on magnetization in CRAZED-multiecho pulse sequence

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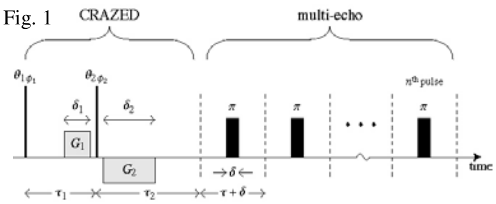
INTRODUCTION

The small intermolecular double quantum coherence (iDQC) signal amplitude has limited its application in most tissues. This may be compensated by multiecho acquisitions, such as echo-planar or fast spin-echo imaging, in the rising period of the dipolar field signal [1]. However the finite duration of refocusing pulses in the multiecho acquisition of iDQC signal leads to significant signal attenuation. Here we explain such phenomenon by evaluating analytically the influence of both distant dipolar field (DDF) and transverse relaxation T_2 on the magnetization (M) in a CRAZED-multiecho pulse sequence (Fig. 1). The obtained expression for the magnetization demonstrates explicitly that the signal rises primarily during the free evolution time in the acquisition period and the signal drop is proportional to the sum of duration of all the refocusing pulses. This elucidates the signal attenuation when the pulses constitute a significant fraction of time in the sequence. From the calculation, we also find that the signal depends substantially on the phases of the rf pulses. In addition, we performed an optimization on the number of refocusing pulses that maximizes the total acquired signal using parameters for water, brain white matter and muscle. We found that maximal signal-to-noise ratio is obtained when the pulse duration approximately equals the free evolution time in the samples with a wide range of T_2.

THEORY

To acquire iDQC signal, we set $G_2\delta_2 = 2G_1\delta_1$. Diffusion is ignored in the CRAZED part of the pulse sequence. In the multiple spin-echo part, it is taken into account through the shortened effective T_2. The flip angle driven by the dipolar field ($\gamma\mu_0 M\delta$) during a refocusing pulse with duration δ is much smaller than π. To the first order of the dipolar field ($\gamma\mu_0 M\delta/\pi$), the Bloch-Torrey equation is solved analytically during the pulse. With $M(\tau_1+\tau_2)$ taken as the initial condition, the magnetization throughout the multiple spin-echo sequence is obtained by repeatedly applying the perturbed result for every π-pulse [2].

Fig. 1



RESULTS AND DISCUSSIONS

The T_2 values used for doped water, white matter and muscle at B_0 = 9.4 T in this abstract are respectively 400 ms, 40 ms and 21 ms. The rf pulses of the CRAZED part have phases ϕ_1 = 0 and ϕ_2 = 0. The calculated magnitude of the normalized spatially averaged transverse magnetization against time for (a) water and (b) muscle are plotted in Fig. 2. The shades in the figure denote the time periods when the refocusing π pulses are applied. The parameter r in the plots is the ratio of the pulse duration (δ) to the pulse separation ($\tau+\delta$), where τ is the free evolution time between two pulses in the multiple spin-echo sequence. The lines with r = 0.01 correspond to the sequences with very short rf pulses. These lines show the unique rising property of iDQC signal ($\propto$ t exp[-t/T_2]) during the free evolution periods between the pulses [3]. When the duration of the rf pulses becomes longer, the transverse magnetization undergoes less free evolution time. The finiteness of the rf pulses decreases the rising time of the signals, so that signals with longer pulses rise less in amount than that with instantaneous pulses. In the situation when the pulses occupy nearly the whole evolution period, $|M_+|$ almost undergoes no free evolution and there is no signal rise. The lines with r = 0.99 in Fig. 2 show the oscillation of the transverse magnetization during the pulse with the envelope governed by T_2 decay. This decay is clearly shown when comparing $|M_+|$ for water and muscle in the figures. The dotted lines in the figures represent the analytical results under linear T_2 approximation, and the dot-dashed lines represent the results with the dipolar field effect excluded during the rf pulses.

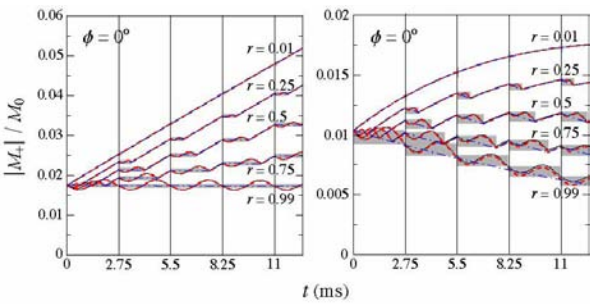


Fig. 2 (a) water (b) muscle

The transverse magnetization at time $t = \tau/2$ after n finite pulses with $n\delta \ll T_2$ and ϕ =0 is [2]

$$M_{+,n} \approx -\tfrac{1}{2}\gamma\mu_0 M_0 m_1(\tau_2+n\tau)e^{-\frac{n\tau}{T_2}}(1-\tfrac{n\delta}{T_2}), \quad (1) \qquad \text{where} \quad m_1 = M_0\cos^2\tfrac{\theta_2}{2}e^{-\frac{\tau_1+\tau_2}{T_2}}. \quad (2)$$

Here m_1 is the conventional signal amplitude ($G_2\delta_2$=$G_1\delta_1$) of the CRAZED sequence, and M_0 is the equilibrium magnetization. Eq.(1) shows the drop of $M_{+,n}$ increases with $n\delta$ as can be seen in Fig. 2.

In the experiment [1], a multiple spin echo acquisition was used to detect the iDQC signal of water. The phases ϕ of the refocusing pulses in the multiple spin-echo sequence are chosen to alternate between 0° and 180° to compensate for the imperfections of the rf pulses. The experimental results are plotted in Fig. 3(a) with a comparison to the theoretical calculations. We attribute the mismatch between the experiment and the calculations to the deviation of ϕ. In Fig. 3(b) we show the calculations with ϕ = 24° and 204°. Obviously the results are in a much better agreement with the experimental data. It was later found that the experiment performed indeed had small hardware-induced phase shifts between high amplitude and low amplitude pulses as predicted above. When the shifts in ϕ were corrected, the experiment gave results in agreement with that described by the calculations in Fig. 3(a).

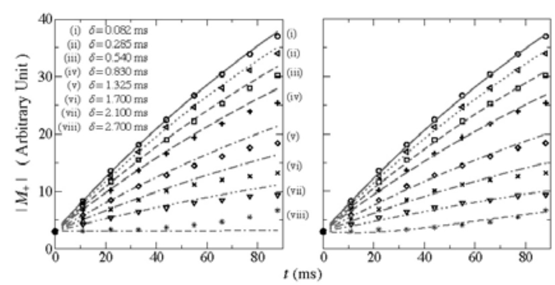


Fig. 3 (a) (b)

The total normalized signal is also calculated by summing all echoes with fixed pulse width δ and fixed duration of the multiple spin-echo sequence T = 40 ms. The pulse separation ($\tau+\delta$) is equal to T/N_π, where N_π is the number of π pulses implemented. Therefore the free evolution time (τ) is given by $\tau = T/N_\pi - \delta$. It can be seen from Fig. 4 that maximum signal-to-noise ratio is acquired when the pulse width is about the same as the free evolution time for a large range of T_2.

In conclusions, we analytically demonstrated how the finiteness of the pulses effectively delays and shortens the rise of the signal. As a consequence, the longer the pulses, the more the signal is attenuated. We found that in the long T_2 limit, the transverse magnetization is proportional to τ exp($-n\tau/T_2$) ($1-n\delta/T_2$). This explains the linear rise of the signal with the total free evolution time and the linear signal attenuation with the total pulse duration as observed in the experiment. We also found that the signal depends substantially on the phase of the refocusing pulses. Finally, the highest total acquired signal in the multiple spin-echo sequence of fixed duration and different pulse widths is obtained when the pulse duration is half of the pulse separation for a large range of T_2.

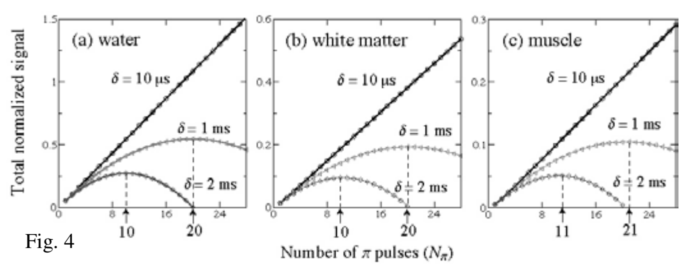


Fig. 4

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[1] S. Kennedy et al., Proc. ISMRM **13**, 2288 (2005). [2] C. K. Wong et al., submitted. [3] J. Jeener in D. M. Grant and R. K. Harris (Eds.), Supplement of the Encyclopedia of Nuclear Magnetic Resonance (Wiley, New York, 2002) p.642.