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Tailored slice selection in solid-state MRI by DANTE under magic-echo line narrowing

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Abstract

We propose a method of slice selection in solid-state MRI by combining DANTE selective excitation with magic-echo (ME) line narrowing. The DANTE RF pulses applied at the ME peaks practically do not interfere with the ME line narrowing in the combined ME DANTE sequence. This allows straightforward tailoring of the slice profile simply by introducing an appropriate modulation, such as a sinc modulation, into the flip angles of the applied DANTE RF pulses. The utility of the method has been demonstrated by preliminary experiments performed on a test sample of adamantane.

Keywords: Slice selection; MRI; DANTE; Magic echo; Line narrowing

1. Introduction

The method of slice selection is well-established in liquid-state MRI. The sinc-shaped soft RF pulse applied in the presence of a field gradient achieves the nearly ideal slice selection. This selection scheme, however, does not work in solid-state MRI where the transverse relaxation time T_2 of the object is much shorter than the soft RF pulse. Although a few slice selection methods have been proposed for solid-state MRI [1–3], each method suffers from its own problem: the method relying on spin locking in the presence of a field gradient exhibits a relatively poor selectivity [1]. The generalized DANTE method combined with multiple-pulse line narrowing is technically demanding [2]. The method using off-resonance spin tipping selects a slice necessarily in the form of longitudinal magnetization [3]. Furthermore, in all the methods proposed so far, the shape of the slice profile is uniquely determined by the method employed and cannot be tailored by the experimenter. These drawbacks seem to have hampered their widespread use in solid-state MRI.

Here, we describe a simple slice selection method for solid-state MRI by combining DANTE selective excitation [4] with magic-echo (ME) line narrowing [5–15]. The new method is technically less demanding, selects a slice in the form of transverse magnetization, and permits tailoring the shape of the slice profile for the first time in solid-state MRI.

2. The ME DANTE method

The original DANTE sequence developed for NMR spectroscopy consists of regularly spaced N short RF pulses. The on-resonance flip angle of each pulse is defined by α_i ($i = 1, 2, 3, \ldots, N$). All the flip angles are identical and the sum of the flip angles is fixed at 90° (Fig. 1). During the pulse spacing τ_D, free precession occurs, leading to the frequency-dependent RF excitation. Since the frequency dependence can be converted to the spatial dependence

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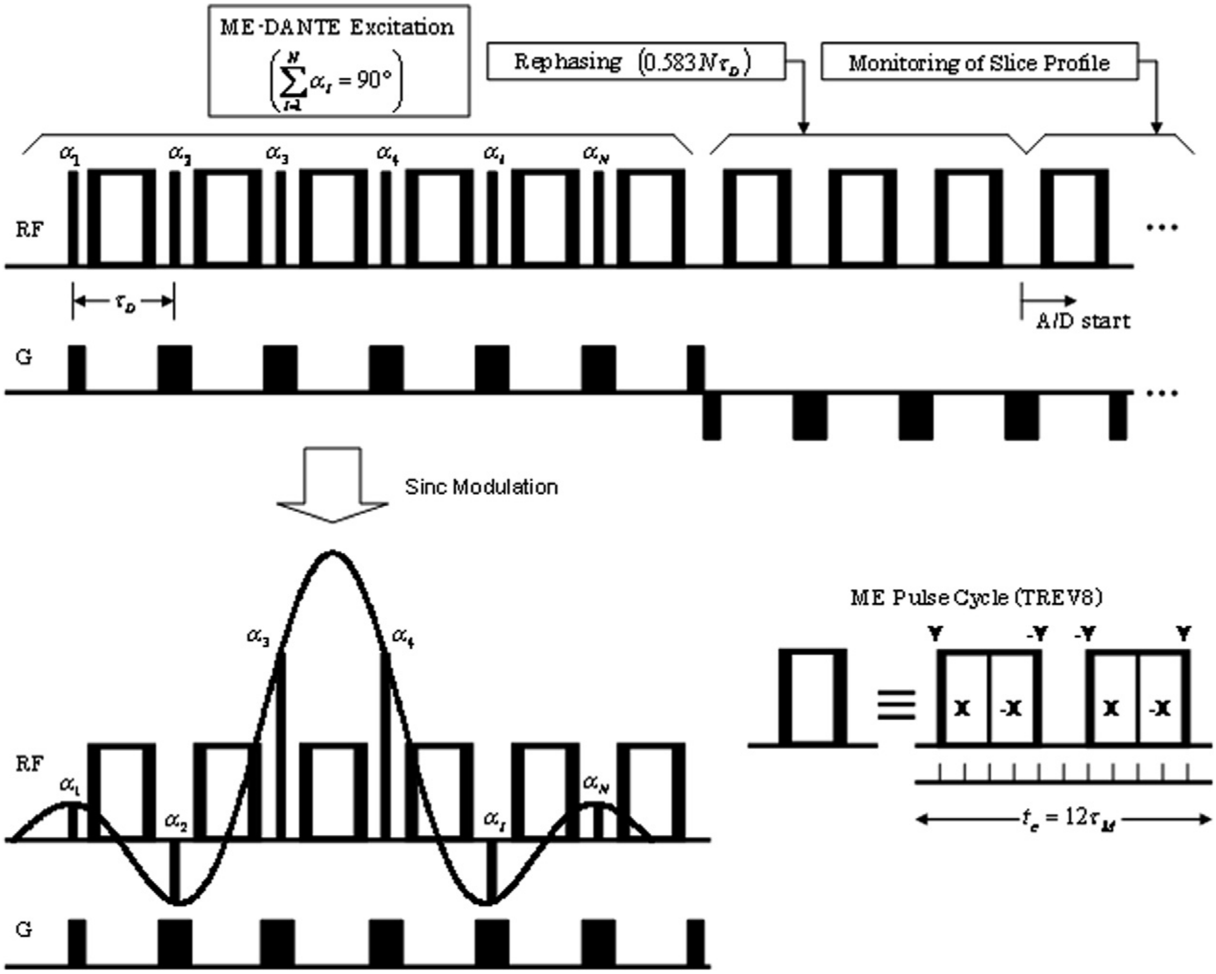

Fig. 1. Pulse sequences for the ME DANTE method of slice selection in solid-state MRI. The sequences comprise two time intervals of ME DANTE excitation and rephasing (for 0.583 $N\tau_D$), followed by the additional sequence for monitoring the profile of the selected slice. Upper sequence: the original DANTE sequence consisting of N identical hard RF pulses (α_i; $i = 1, 2, 3, \ldots, N$) is combined with the ME line narrowing sequence. The DANTE RF pulses are applied at ME peaks every pulse cycle of TREV8 ($\tau_D = t_c$) so as to avoid their interference with the ME line narrowing. Lower sequence: a sinc modulation is introduced into the DANTE sequence by changing the flip angles appropriately for tailoring the slice profile. Field gradient pulses G are applied for transforming the frequency response of the DANTE sequence to the spatial response. The gradient pulses are inverted during the second time interval for rephasing by means of gradient echo. In the middle of the pulse cycle TREV8, signal sampling is made and a gradient pulse is applied despite not indicated explicitly. The α_i pulse amplitudes are depicted exaggerated; the maximum amplitude is the same as that of 90° pulses in the ME sequence.

by application of a field gradient G, slice selection can be attained by the DANTE sequence.

The regular spacing of the DANTE hard-pulse sequence makes it ideally suited for the combination with the ME sequence which is cyclic. For combining the DANTE sequence with the ME line narrowing sequence without lowering the line narrowing efficiency, it is necessary to apply the DANTE RF pulses at the ME peaks where the time evolution of the spin system is free from the dipolar interaction. This point is discussed below in comparison with similar approaches employing the multiple pulse sequences for line narrowing.

The combined ME DANTE pulse sequence is represented by the upper sequence in Fig. 1. The field gradient pulses G are applied for the conversion from the frequency to the spatial discrimination. The ME DANTE excitation is followed by the ME sequence with reversed gradient pulses for rephasing the signal, similarly as in the soft RF pulse excitation commonly used for liquid-state MRI [16]. The optimal rephasing was evaluated by numerical simulation based on the Bloch equations [16]. It has been found that the rephasing can be optimized by reversing the gradient G for 0.583 $N\tau_D$ following the excitation (Fig. 1). (We did not employ the analytical expression [17] for the simulation because the numerical simulation was more suitable for evaluating the optimal rephasing.) The rephased signal is then detected by the 1D ME imaging sequence (A/D start) for monitoring the slice profile. The TREV8 [6] was employed as the ME pulse cycle, since it is compact and exhibits a reasonably good line-narrowing efficiency. The cycle time $t_c = 12\tau_M$ was set equal to the DANTE pulse spacing τ_D. All the DANTE RF pulses are applied along the x axis in the rotating frame.