ARTICLE IN PRESS

Magnetic Resonance Imaging xxx (2013) xxx–xxx

Contents lists available at ScienceDirect

Magnetic Resonance Imaging

journal homepage: www.mrijournal.com

Online tool for calculating null points in various inversion recovery sequences

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A R T I C L E   I N F O

Article history:
Received 8 February 2013
Revised 26 June 2013
Accepted 26 June 2013
Available online xxxx

Keywords:
Inversion recovery (IR)
Null point
Equation
Spectral attenuated inversion recovery (SPAIR)
Diffusion-weighted imaging (DWI)
Magnetic resonance (MR)

A B S T R A C T

Accurate equations for calculating the inversion time of the null point (TI_{null}) in inversion recovery (IR) sequences are required for adequate suppression of fat or cerebrospinal fluid (CSF) but are not widely known. The purpose of this study is to elucidate the process of deriving accurate TI_{null} equations using schematic diagrams that allow the equations to be easily understood, and to devise a convenient online tool for instant calculation of TI_{null}.

We investigated various IR sequences in which a 180° inversion pulse is followed by spin echo (SE) type sequences, termed IR–SE-type sequences, including FLAIR (fluid attenuated inversion recovery), STIR (short inversion time inversion recovery), and SPAIR (spectral adiabatic inversion recovery, spectral attenuated inversion recovery). We classified these sequences into three types according to the behavior of the longitudinal magnetization before the next IR pulse: having a train of multiple spin echoes, a single spin echo, or a train of multiple inversions by SPAIR pulses (with no spin echo). For each sequence type, we produced a precise diagram of the behavior of the longitudinal magnetization and clarified the process of deriving the equation for TI_{null}. Three accurate TI_{null} equations were derived. We created an online tool that calculates TI_{null} using these three equations. The validity of the resulting TI_{null} was evaluated on pelvic SPAIR diffusion-weighted (DW) images at 3 T in 21 volunteers, using various inversion times (TI) around the calculated TI_{null}.

The tool displays the calculated TI_{null} value instantly, after inputting imaging parameters and the T_1 values of fat or CSF. The TI_{null} values calculated using the tool achieved sufficient suppression in all subjects. When the actual TI value differed by more than 5% from the calculated TI_{null} value, the fat suppression effect was significantly less on pelvic SPAIR DW images ($P < 0.01$).

In conclusion, this online tool is easily available and enables adequate suppression of fat or CSF according to the imaging parameters.

1. Introduction

It is important to optimize the inversion time of the null point (TI_{null}), which corresponds to the time when the longitudinal magnetization of fat or cerebrospinal fluid (CSF) is zero, in order to adequately suppress fat or CSF signal, in inversion recovery (IR) sequences such as FLAIR (fluid attenuated inversion recovery), STIR (short inversion time inversion recovery), and SPAIR (spectral adiabatic inversion recovery, spectral attenuated inversion recovery). TI_{null} is commonly determined by experience [1] or by the well-known equation: $TI_{null} = T_1 \cdot \ln 2$ [2], where T_1 is the longitudinal relaxation time. However, this equation is incorrect if the repetition time (TR) is not much longer than T_1 [1,2].

If the inversion time is not optimized when the imaging parameters are modified, adequate suppression cannot be obtained (Fig. 1 A, B).

In diffusion-weighted imaging (DWI) at 3 T, a spectral–spatial excitation pulse does not always yield adequate fat suppression because of the high sensitivity of the pulse to B_0/B_1 inhomogeneity. STIR-DWI is commonly used under conditions of strong B_0 inhomogeneity, but it has a low signal-to-noise (S/N) ratio. Therefore, SPAIR-DWI can be useful for 3 T imaging because it retains a high S/N ratio and has an adiabatic pulse that is insensitive to B_1 inhomogeneity. However, if the inversion time does not coincide with the null point, adequate suppression cannot be obtained: DWI commonly exhibits distinctive chemical shift artifact

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http://dx.doi.org/10.1016/j.mri.2013.06.014

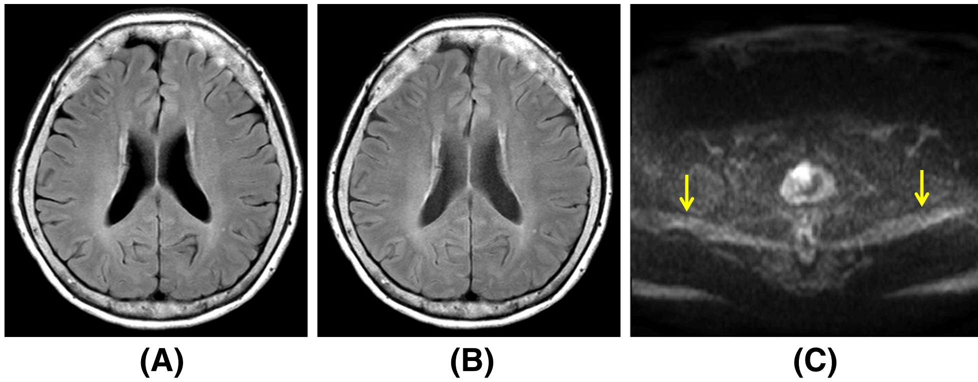

Fig. 1. Example images obtained using default TI values. (A) FLAIR-TSE brain image at 3 T using default parameters (TR/TI = 11000/2800 ms) shows adequate suppression of CSF. (B) FLAIR-TSE brain image at 3 T using modified TR and default TI (TR/TI = 8000/2800 ms) shows inadequate suppression of CSF. (C) SPAIR DW pelvic image at 3 T using default parameters (TR_{SPAIR}/TI = 209/90 ms) shows inadequate suppression of fat with distinctive chemical shift artifact (arrows) superimposed on the image.

(CSA) superimposed on the image (Fig. 1C). CSA, which is caused by unsuppressed fat signal, appears as markedly high signal intensity with pronounced fat shift in the phase-encoding direction. The high signal intensity is caused by the very low diffusion coefficient of fat [3,4]. The pronounced fat shift occurs in the phase-encoding direction because of the low bandwidth in this direction in echo planar imaging (EPI) [5]. Accordingly, accurate calculation of TI_{null} is required.

A small number of accurate TI_{null} equations that always hold are reported for a small number of pulse sequences [2,6–8]. However, the accurate equations are not widely comprehended because of their complexity and because few readily understandable explanations of their derivation are reported.

The purpose of this study is to provide an easily understandable explanation of the process of deriving accurate TI_{null} equations for various IR sequences in which a 180° inversion pulse is followed by spin echo (SE) type sequences, termed IR–SE-type sequences, and to make the equations readily accessible for clinical application. We classified various IR–SE-type sequences into three types according to the behavior of the longitudinal magnetization. We produced precise schematic diagrams of the behaviors of the longitudinal magnetization, elucidated the process of deriving TI_{null} equations, and derived three accurate TI_{null} equations. We devised a convenient online tool employing these three equations that can be used to instantly calculate TI_{null} whenever the imaging parameters are modified. We also verified the validity of this tool for 3 T SPAIR-DWI, in which adequate fat suppression is difficult to obtain.

2. Materials and methods

The study was performed on a 1.5 T MR scanner (MAGNETOM Symphony; Siemens, Germany) and a 3 T MR scanner (Achieva X-series; Philips, The Netherlands) installed at our institute.

Using these MR scanners, we investigated the null points of fat and CSF in the various IR–SE-type sequences, in which a 180° inversion pulse is followed by SE, turbo-SE (TSE), and SE-EPI sequences (Table 1).

2.1. Derivation of TI_{null} equations

The relaxation of longitudinal magnetization (M_z) under B_0 applied along the z-axis is described by the Bloch equation:

$$\frac{dM_z}{dt} = -\frac{M_z - M_0}{T_1} \quad (1)$$

where M_0 is longitudinal thermal equilibrium magnetization. Longitudinal magnetization at time t, $M_z(t)$, is derived from the Bloch equation as follows:

$$M_z(t) = M_0 - (M_0 - M_z(0)) \cdot \exp\left(-\frac{t}{T_1}\right) \quad (2)$$

where $M_z(0)$ is the longitudinal magnetization at $t = 0$.

Eq. (2) represents the exponential recovery of longitudinal magnetization from $M_z(0)$ to $M_z(t)$ with time constant T_1, during the time from 0 to t. That is, when $M_z(0)$ is known, $M_z(t)$ can be derived from Eq. (2). Eq. (2) can be used as the basic formula for mathematically expressing the behaviors of longitudinal magnetization.

First, we consider the null point when the longitudinal magnetization just before the IR pulse is equal to M_0; i.e., when the 1st excitation is applied or when TR is much longer than T_1. Assuming the inversion pulse is perfect, M_0 is inverted to become $-M_0$. At the time of the null point, by substituting $t = TI_{null}$, $M_z(0) = -M_0$, and $M_z(TI_{null}) = 0$ into Eq. (2), TI_{null} can be expressed as follows:

$$TI_{null} = T_1 \cdot \ln 2, \quad (3)$$

which is the well-known TI_{null} equation but holds only when TR is much longer than T_1; that is, only when the longitudinal magnetization recovers to M_0 before the IR pulse [1,2].

Hereafter, we consider accurate equations for TI_{null} that always hold, even when TR is not much longer than T_1, which is the main purpose of this study.

Multiple excitations including dummy scans are repeated in most pulse sequences. When TR is not much longer than T_1, the longitudinal magnetization just before the next IR pulse is less than M_0. Because this lesser magnetization is inverted, the null point comes earlier than $T_1 \cdot \ln 2$; i.e., $TI_{null} \leq T_1 \cdot \ln 2$.

Table 1
Classification of IR–SE-type sequences according to the behavior of longitudinal magnetization (M_z) before the next IR pulse.

Behavior of M_z before the next IR pulse	IR–SE-type sequences
Multiple spin echoes	FLAIR-TSE, STIR-TSE, 3D SPAIR-TSE, 2D single-slice SPAIR-TSE
Single spin echo	STIR-DWI, FLAIR-SE, STIR-SE, 2D single-slice SPAIR-DWI
Multiple inversions by SPAIR pulses	2D multi-slice SPAIR-TSE, 2D multi-slice SPAIR-DWI