Time-efficient Multislice Black-blood Imaging with Reduced Field-Of-View using Quadruple Inversion-Recovery Sequence

V. L. Yarnykh[1], C. Yuan[1]

[1]Radiology, University of Washington, Seattle, WA, United States

Introduction: Improvement in time efficiency of back-blood imaging is an important goal in modern pulse sequence design for cardiovascular MRI. A double inversion-recovery (DIR) (1) blood suppression technique is frequently used as a robust and reliable method, but has a major limitation of being extremely time-inefficient due to its inherent single-slice acquisition. Recently proposed multislice DIR (MDIR) methods (2-5) can overcome this limitation, although their time performance is somewhat limited by relatively long inversion delays and outflow requirements. Another way to improve time efficiency of black-blood imaging is the use of reduced field-of-view (FOV) methods, which employ selective excitation or outer volume suppression to reduce the number of phase-encoding steps (6-8). A recently presented FOV-reduction method originally named SFQIR (small-FOV Quadruple Inversion-Recovery) (8) utilizes a preparative sequence of four inversion pulses to achieve simultaneous outer volume and blood suppression. This method is based on a previously proposed QIR technique for T_1-insensitive blood suppression (9). Here we present a multislice extension of this technique, which enables considerable time savings by combining the above principles, i.e. multislice acquisition and FOV reduction.

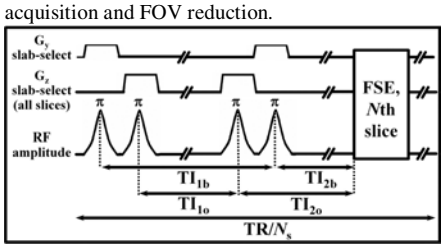

Fig. 1. The MSFQIR preparative sequence.

Methods: A new multislice SFQIR (MSFQIR) pulse sequence employs the SFQIR (Fig. 1) preparation consisting of two double-inversion pulse pairs following by inversion delays. This preparative module is executed before a fast spin-echo (FSE) readout sequence. Within each pair, inversion pulses are successively applied to two slabs: Z-slab is composed of all imaged slices, and Y-slab is orthogonal to the imaging plane with the thickness equal to the FOV size in the phase-encoding direction. Each double inversion results in reinversion of the magnetization in the central part of the FOV, while the outer areas of the FOV (termed below as "outer volume") and inflowing blood within Y-slab remain inverted. The sequence in Fig. 1 is repeated for each slice within the TR interval. Consider effect of this sequence on the outer volume and inflowing blood. For the outer volume, the total sequence of RF pulses and delays acting on a particular slice within the time TR can be expressed as follows:

$$\mathbf{180^o - TI_{1o} - 180^o - TI_{2o} - 90^o - (\tau - \beta^o - \tau)}N - T_{D1o} - (180^o - TI_{1o} - 180^o - T_{D2o})(N_s\text{-}1),$$

where N is the echo train length, the echo spacing is expressed as 2τ, β is the flip angle of a refocusing pulse, N_s is the number of slices, T_{D1o} = TR/N_s - $2N\tau$ - TI_{1o} - TI_{2o}, and T_{D2o} = TR/N_s - TI_{1o}. Of note, inversion delays for the outer volume ($TI_{1,2o}$) and blood ($TI_{1,2b}$) (Fig. 1) are different due to non-negligible duration of an adiabatic inversion pulse (~10 ms). The outer volume experiences one repetition of the FSE sequence and N_s repetitions of the dual inversion preparative sequence per TR. There are also two delays: the post-acquisition delay T_{D1o} is applied once per TR when the particular slice is imaged, and a longer delay T_{D2o} is applied N_s-1 times when the FSE imaging sequence is applied to other slices. Consecutive solution of Bloch equations for the above pulse sequence results in the expression for the longitudinal magnetization before the 90º excitation pulse:

$$M_{zo} = 1 - F\exp(-(\mathrm{TR} - 2N\tau)/T_1) - 2\exp(-\mathrm{TI}_{2o}/T_1)[1-\exp(-\mathrm{TI}_{1o}/T_1)][1-\exp(-\mathrm{TR}/T_1)]/[1-\exp(-\mathrm{TR}/(N_sT_1))], \quad [1]$$

where $F = [(\cos\beta)^N E^{2N}(1-E)(1+E\cos\beta) + E(1-\cos\beta)]/[1-E^2\cos\beta]$

with E defined as E=exp(– τ/T_1). Based on this model, optimal inversion times corresponding to the maximal suppression efficiency can be found by minimization of the variation of the normalized signal over the entire range of T_1 occurring in tissues using the previously described algorithm (9). The magnetization of inflowing blood within the Y-slab is periodically inverted with delays between inversion pulses TI_{1b} and TR-TI_{1b}. The behavior of the blood signal is described by the equation:

$$M_{zb} = 1 - 2\exp(-\mathrm{TI}_{2b}/T_1)[1-\exp(-\mathrm{TI}_{1b}/T_1)]/[1-\exp(-\mathrm{TR}/(N_sT_1))] \quad [2]$$

This is similar to the equation for the QIR sequence (9), where the repetition period for pulses acting on the blood magnetization is equal to TR/N_s instead of TR. The MSFQIR sequence was implemented on a 1.5T MR scanner (GE Signa). Suppression efficiency was tested with a phantom containing media with different relaxation properties: T_1=203, 392, 754, 246, and 2570 ms. The MSFQIR technique was compared to the MDIR method (4) in vivo for imaging of the aorta in three healthy subjects.

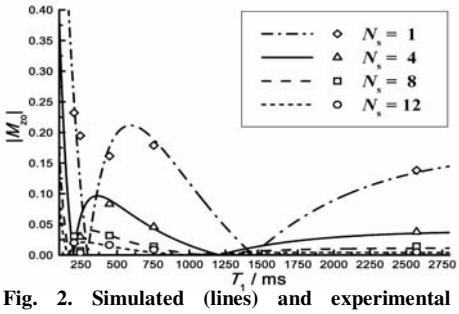

Fig. 2. Simulated (lines) and experimental (points) magnetization of the outer volume (absolute values) as a function of T_1 for variable number of slices N_s and corresponding optimal TI_{1o} and TI_{2o}: N_s=1, TI_{1o}/TI_{2o}=1307/189 ms (dash-dot and diamonds); N_s=4, TI_{1o}/TI_{2o}=564/107 ms (solid and triangles); N_s=8, TI_{1o}/TI_{2o}=320/70 ms (long-dash and squares); and N_s=12, TI_{1o}/TI_{2o}=224/51 ms (short-dash and circles). For all plots TR=4000 ms, N=8, and 2τ=7.9 ms.

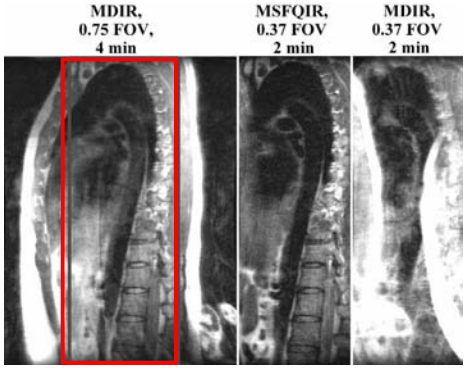

Fig. 3. Black-blood MR angiography of the aorta using MDIR (left and right) and MSFQIR (center) methods with FSE readout (TR/TE=6800/11.5 ms, ETL=16, slice thickness 4 mm, NEX=2, 12 slices per TR). Red frame shows the reduced FOV size and the right image illustrates aliasing artifacts occurring without MSFQIR preparation. All images were obtained with free-breathing non-gated acquisition.

Results: Simulations and phantom experiments (Fig. 2) suggest that efficient outer volume suppression (<2-5% of the residual signal) can be simultaneously obtained for the virtually whole range of T_1 expected in biologic tissues (200-3000 ms) at any TR. The suppression efficiency is determined by the repetition time per slice, TR/N_s. For a fixed TR, an increase of the number of slices results in improved suppression (Fig. 2). The optimal choice of TR/N_s is 400-800 ms that provides a tradeoff between the suppression efficacy and unwanted saturation of an imaged region by multiple inversion pulses. In vivo imaging of the aorta with MSFQIR demonstrated an about 50% scan time reduction as compared to MDIR (4) with similar parameters due to the reduction of the FOV size (Fig. 3). The MSFQIR image (Fig. 3) shows effective removal of the strong signal in regions proximal to the surface coil. Important advantages of the MSFQIR method are the elimination of motion artifacts originating from the chest wall and heart and an improvement in blood suppression due to bi-directional in-flow saturation.

Conclusions: MSFQIR is a new time-efficient technical solution for multislice black-blood imaging, which provides additional capabilities of outer volume suppression. These include elimination of motion artifacts, suppression of in-plane blood flow, reduction of scan time, and possibility to improve spatial resolution.

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