Simulations of Motion-Insensitive Diffusion Imaging Based on the Distant Dipolar Field

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Introduction

Diffusion weighting in MRI is commonly achieved with the pulsed-gradient spin-echo (PGSE) method. However, images acquired by this method often exhibit ghosts because of sample's macroscopic motion. These motion artifacts can be mostly eliminated by using the distant dipolar field (DDF) method, which relies on the refocusing of spatially modulated transverse magnetization by the DDF within the sample itself [1]. In this report, DW images using both DDF and PGSE method were simulated. The results demonstrate that with the equivalent diffusion weighting, DW-DDF images are much less sensitive to the macroscopic sample motion, and thus have fewer motion artifacts than traditional DW-PGSE images.

Simulation methods

DW MRI signals were simulated by three-dimensioned integration calculations of the time evolution of magnetization under the nonlinear Bloch equations. The effects of relaxation, diffusion, chemical shift, and distant dipolar field were all incorporated into the Bloch equations [2]. In addition, to describe the effects of motion, Fourier imaging mechanism was also simulated. The sample shown in Fig. 1 was a large cylinder consisting of 12×12×24 grid points inside a 32×32×32 point array (the distance between two adjacent points is 20 μm). The basic parameters for the cylinder were: magnetization density M_0 = 0.023 A/m, T_1 = 1 s, T_2 = 0.1 s, diffusion coefficient D_T = 0, chemical shift ω = 0. M_0 = 0 for points surrounding the sample (empty space). A smaller cylinder (shaded, 6×6×24 grid points) with identical parameters but a different diffusion coefficient, $D_T = 3.0 \times 10^{-9}$ m/s^2 was inside the larger cylinder. The pulse sequences used in simulation were the standard DW-PGSE image sequence and DW-DDF sequence shown in Fig. 2. To achieve an equivalent diffusion weighting (~40% signal reduction) [3], the parameters of DW-PGSE sequence were: Δ = 26 ms, δ = 1 ms, G_D = 30 G/cm, and those of DW-DDF sequence were: TE = 80 ms, $d_c = \pi/\gamma G\delta$ = 60 μm. During the course of imaging with these two pulse sequences (TR = 3.5 s), the sample was assumed to move periodically along the z axis following a sine velocity function, mimicking the motions such as heartbeat or breathing in the human. Two motion modes were simulated, one with the motion frequency constant (1.25 Hz) while the maximum motion amplitude was 1.9, 2.0, or 2.2 mm (Fig. 4); the other with the motion amplitude constant (2.0 mm for DW-PGSE and 4.0 mm for DW-DDF) while the motion frequency increased from 1.25, 1.58, to 2.10 Hz (Fig. 5).

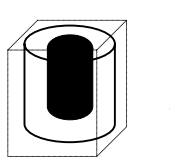

Fig. 1 Sample used in the simulation

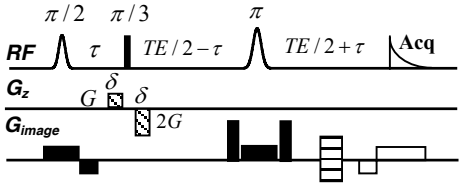

Fig. 2 DW-DDF image pulse sequence

Results and discussion

As shown in Fig. 3, the diffusion weighting results in ~40% signal reduction in the centric areas compared to the rest areas (D_T = 0) around them in both motion-free DDF and PGSE images. When the motion frequency is constant, the motion artifacts along the phase-encoding (PE) direction increase with the increasing of motion amplitude of the sample (Fig. 4). In the DW-PGSE images (a-c), the ghosts are so strong that the primary image is hardly distinguishable from them. However, the motion artifacts in the DW-DDF images (d-f) are barely observable. Similarly, when the motion amplitude is constant and the motion frequency increases, motion artifacts in the DW-DDF images are much less pronounced than in the DW-PGSE images, even though the motion amplitude of the sample for DW-DDF images is twice that for DW-PGSE images in these simulations (Fig. 5).

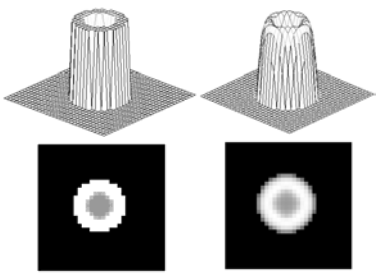

Fig. 3 (a) DWI-PGSE; (b) DWI-DDF. The signal of the centric areas is reduced ~40% due to diffusion when the sample is immobile.

It is well known that motion induced phase shift causes the appearance of ghosts along the PE direction. Our simulated results demonstrate that with the equivalent diffusion weighting, DW-DDF images have much less artifacts resulted from sample motion than DW-PGSE images. This is because that the refocusing effect of modulated magnetization in DW-DDF image is DDF carried within the sample, and not external gradient field produced by gradient coils in conventional DW-PGSE imaging. Consequently, in DW-DDF imaging, the macroscopic motion does not alter the DDF inside the sample, thus does not interfere with signal formation; while in DW-PGSE imaging the sample motion often causes the true DWI signals indistinguishable from motion artifacts. Taking advantage of the unique property that the signal due to distant field effects is insensitive to the macroscopic motion of sample, DW-DDF image method may redound to the use of DWI in motion-prone regions such as heart, lungs, and abdomen [3].

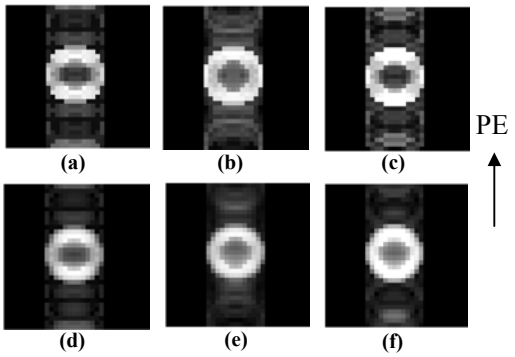

Fig. 5 (a-c): DWI-PGSE; (d-f): DWI-DDF. The motion amplitude is constant (2.0 mm for DWI-PGSE, 4.0 mm for DWI-DDF), and the motion frequencies are 1.25 Hz (a,d), 1.58 Hz (b,e), and 2.10 Hz (d,f), respectively.

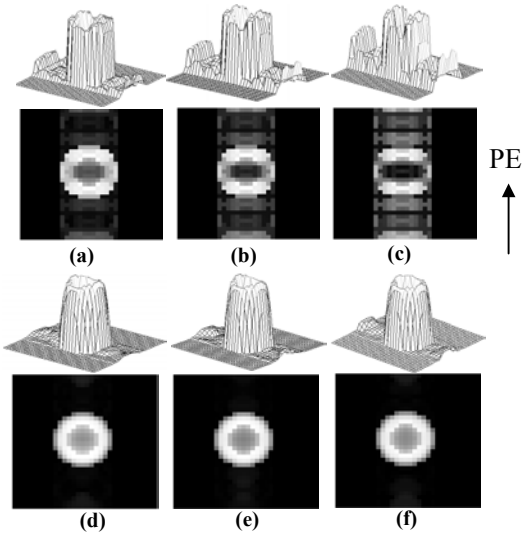

Fig. 4 (a-c): DWI- PGSE; (d-f): DWI- DDF. The motion frequency is 1.25 Hz and the motion amplitudes of the sample are 1.9 mm (a,d), 2.0 mm (b,e), and 2.2 mm (d,f), respectively.

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References

[1] Robyr P, et al. ***J. Magn. Reson.*** 121 (1996) 206. [2] Enss T, et al. ***Chem. Phys. Lett.*** 305 (1999) 101. [3] Kennedy SD, Zhong J. ***Magn. Reson. Med.*** 52 (2004) 1.