Diffusion-prepared multi-shot bSSFP imaging with gradient stabilizer

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Synopsis

A gradient stabilizer strategy was proposed to solve the k-space magnitude inconsistency problem in multi-shot diffusion-prepared bSSFP imaging. Simulation studies showed that the proposed approach is insensitive to phase errors during the diffusion encoding stage, and has built-in fat-saturation property. Phantom and in-vivo studies verified that adding gradient stabilizers could remove signal loss and artifacts, and provide repeatable artifact-free images. Combined with existing phase correction techniques, the proposed approach provided distortion-free high-quality 2D diffusion-weighted and diffusion tensor images, and has the potential of extending to 3D.

Introduction

Diffusion-prepared imaging approach is gaining popularity due to its flexibility of combining with any types of readout including balanced steady-state free precession(bSSFP), which has the promise of achieving fast 3D multi-shot distortion-free diffusion[1]. However, shot-to-shot inconsistency is inevitable in multi-shot diffusion-weighted imaging. Even in the brain, phase inconsistency caused by eddy currents and non-rigid pulsatile motion could lead to destructive signal loss and ghosting artifacts that cannot be easily resolved by low-order motion compensation. Various reconstruction methods have been proposed to mitigate the phase variation problem in diffusion-weighted approach[2,3]. However, in diffusion-prepared approach, the use of spoilers after the -90˚ tip-up pulse induced a shot-to-shot magnitude inconsistency. This magnitude variation is more challenging to be alleviated due to the complementary parts have already been spoiled. In this work, we propose to use a gradient stabilizer approach to convert the magnitude problem back to the well-studied phase problem. In this way, the images can be reconstructed using existing well-developed methods.

Methods

Sequence: Figure 1(a) shows the sequence diagram of the proposed gradient-stabilized diffusion-prepared bSSFP sequence (GS-DP-bSSFP, abbreviated as GS-DP. Sequence without GS is abbreviated as DP). Inspired by Alsop[4], one 4π dephasing gradient is placed before the -90˚ pulse. Rephrasing and dephasing gradients are played during each readout. As illustrated in Figure 1(b)-(c), those gradients convert the magnitude inconsistency back to the phase inconsistency in diffusion-prepared acquisition.

Simulation: Bloch simulations and Spin Bench simulation(HeartVista, Mountain View) were performed to simulate the effect of adding gradient stabilizers with respect to phase error and off-resonance. In the first simulation, a -π to π phase error was added before the -90˚ pulse to 1000 simulated spins. Signal magnitude of the first echo was plotted. In the second simulation, 440Hz off-resonance(off-resonance of fat at 3T) was studied. Signal magnitude during the echo train with and without GS and with and without off-resonance was compared.

Phantom: A diffusion phantom with a fat tube on top was used to quantify the ADC accuracy of the proposed GS-DP sequence. TSE, diffusion-weighted single-shot EPI(DW-ssEPI), DP, and GS-DP images were acquired on a 3T scanner(Prisma, Siemens) with the following parameters: Resolution=1.0x1.0mm^2/1.9x1.9mm^2/1.2x1.2mm^2/1.2x1.2mm^2, TE=85ms/97ms/45ms/45ms, number of shot=16/1/4/4, and TR=3ms for the four sequences mentioned above respectively. B-values of 0, 200 and 500 s/mm^2 were acquired in the three diffusion sequences. Fat-saturation was only applied in the DW-ssEPI scan.

In-vivo study: Five healthy volunteers were recruited to evaluate the in-vivo feasibility. To study the benefits of the proposed approach, DP without ECG gating, DP with ECG gating, and GS-DP without ECG gating were acquired ten times with b=500s/mm^2 in a single-shot manner. To evaluate the multi-shot feasibility, DW-ssEPI and 4-shot GS-DP (no ECG) were acquired with b=0, 200 and 500 s/mm^2. In one volunteer, 4-shot GS-DP with b=500s/mm^2 was acquired along 15 directions for the diffusion tensor reconstruction. All multi-shot GS-DP images were reconstructed using the MUSE technique[3].

Results and Discussion

Without gradient stabilizers (Figure 2(a)), the signal magnitude exhibited a strong dependence on the phase error. Adding gradient stabilizers maintained the signal magnitude but with the price of half of signal loss. Figure 2(b) is the off-resonance simulation. At 440Hz off-resonance, the signal magnitude in DP was approximately three times higher than the 0Hz case and had strong oscillation; whereas in GS-DP, the signal is suppressed at 440Hz.

As shown in Figure 3, the proposed GS-DP approach had substantially reduced distortion and susceptibility-related artifacts compared to DW-ssEPI. Susceptibility related artifacts around the tube/phantom boundary were also reduced compared to DP. The fat tube produced a negligible signal in GS-DP although no fat saturation was applied. This is consistent with the simulation result shown in Figure 2(b). For tubes that has diffusivity over 0.5x10^{-3} mm^2/s, the ADC difference between DW-ssEPI and GS-DP was within 4%.

Without GS and ECG gating, the images had severe signal void artifacts (Figure 4). Those magnitude variations were hard to compensate due to the complementary parts have already been spoiled. ECG gating could reduce the artifacts; however, magnitude variations were still observable. Adding the gradient stabilizer provided stable signal magnitude across all repetition which is essential for high-quality multi-shot imaging.

Multi-shot images from two volunteers are shown in Figure 5. Distortion and susceptibility-related artifacts were substantially reduced using the GS-DP approach. For selected ROIs on the grey matter, white matter and CSF, ADC differences between GS-DP and DW-ssEPI were within 5%. High-resolution high quality color-coded fractional anisotropy map was generated using the GS-DP approach.

Conclusion

The proposed GS-DP approach provided high-quality 2D multi-shot diffusion images and has the potential of achieving fast 3D distortion-free diffusion imaging.

Acknowledgements

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References

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Figures

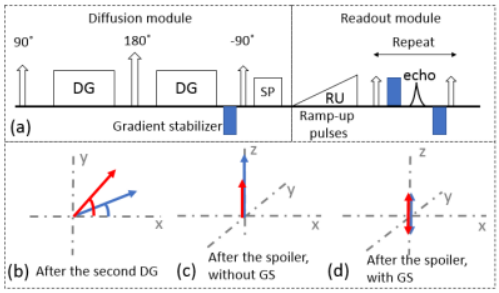

Figure 1.(a) Sequence diagram of one shot. Blue rectangle represents the gradient stabilizer (GS). (b) Illustration of magnetizations after the diffusion gradients for two different shots (blue and red arrows). (c-d) Magnetizations for the two shots after the spoilers without and with GS. Without GS, only x component in (b) is flipped to the z-direction, while the y component is destroyed by the spoilers, causing magnitude inconsistency. With GS, half of the magnetization is flipped to the z-direction no matter of the phase angles in (b). The phase difference is stored and will be reformed after rewinding the gradient stabilizer.

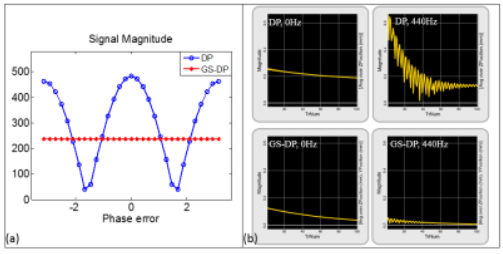

Figure 2. (a). Simulation of adding phase error before the tip-up pulse. (b) Simulation of off-resonance effect. Adding phase error does not affect the magnitude in GS-DP approach, whereas could cause signal oscillation in DP approach. At 440Hz, DP produced strong and oscillating signal magnitude. On the contrary, the signal magnitude was around 7 times lower than the 0Hz case.

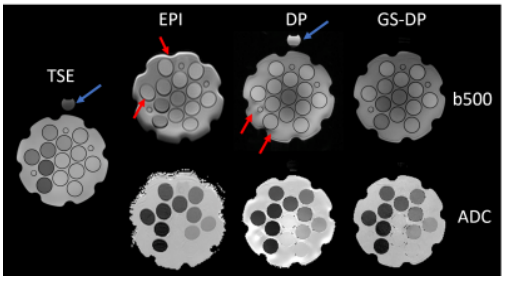

Figure 3. Phantom images. TSE was acquired as the geometric reference. B500 images and ADC maps from DW-ssEPI, DP, and GS-DP were shown. The blue arrows point to the fat tube which was suppressed in GS-DP although no fat-saturation was applied. The red arrows point to distortion and susceptibility artifacts in DW-ssEPI and susceptibility artifacts in DP.

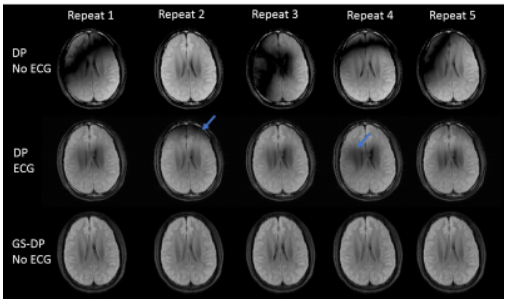

Figure 4. Single-shot in-vivo images from DP without ECG gating, DP with ECG gating and GS-DP without ECG gating. Five repetitions were shown. Signal void artifacts were strong in DP no ECG case. Adding ECG gating could mitigate the artifacts but did not eliminate it as shown by the blue arrows. No magnitude variation was observed in GS-DP images.

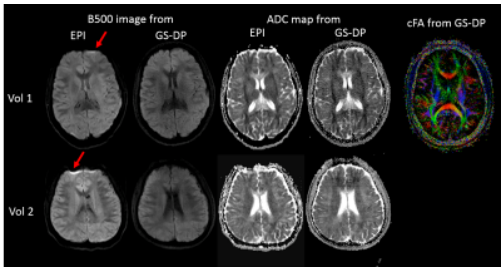

Figure 5. Multi-shot in-vivo results from two volunteers. B500 images and ADC maps from DW-ssEPI and GS-DP, and color-coded fractional anisotropy (cFA) map from GS-DP were shown. In the cFA map, the major eigenvector directions are indicated by different colors and weighted by the FA (red: left/right, blue: superior/inferior, and green: anterior/posterior). The red arrows point to distortion and susceptibility related signal pile-up in DW-ssEPI images. No artifact was observed in GS-DP images.