Three-Dimensional Diffusion-Prepared Balanced Steady-State Free Precession with Variable Flip Angle Scheme

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Target Audience: Scientists and engineers who have an interest in three-dimensional diffusion weighted imaging.

Purpose: Diffusion preparation is useful for multi-shot diffusion weighted pulse sequences due to its robustness to motion. [1, 2] If the T1 recovery time of a subject is not negligible, its modulation of the k-space signal results in image degradation. Variable flip angles can modulate MR signal levels in an echo train to improve the modulation transfer function. [3] The purpose of this work was to develop and demonstrate the feasibility of 3D diffusion-prepared balanced steady-state free precession (DP-bSSFP) pulse sequence with a variable flip angle technique.

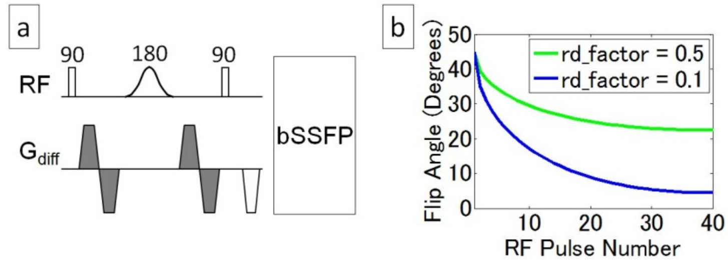

Fig. 1 Schematic of the DP-bSSFP with bipolar diffusion gradient (shaded) and the bSSFP RF flip angle trains.

Methods: *Pulse Sequence Design:* The DP-bSSFP pulse sequence was developed by combining a non-slice-selective diffusion preparation (90-180-90) with a 3D bSSFP shown in Figure 1. Preparation pulses consisted of excitation RF (90x), refocusing RF (180y), tip-up RF (90x-), motion probing gradient (MPG), and spoiling gradient pulses. The diffusion preparation had bipolar motion probing gradients to reduce artifacts caused by bulk motion. [2] The bSSFP sequence followed diffusion preparation with the echo train length ETL and the maximum flip angle α_{max}. An RF pulse of $\alpha_{max}/2$ was applied at a time TR/2 before the first α RF pulse for quick steady-state restoration. To correct for signal increase with T1 recovery, the flip angle was decreased progressively with the equation

$$\alpha_n = \alpha_{max}\left[1-(1-rd\_factor)\sin\left(\frac{\pi}{2}\sqrt{\frac{n-1}{ETL-1}}\right)\right] \quad [1]$$

where rd_factor is a ratio of the last flip angle to α_{max}, and n is the echo number, respectively. Figure 2 shows sample flip angle trains with rd_factors of 0.5 and 0.1. Each echo train acquired half a kz line data with a centric view ordering in the ky direction positively or negatively. After the whole k-space data was acquired, data acquisition was repeated with the different phases (120° and 240°) of the diffusion preparation tip-up RF pulse. After the inverse Fourier transform, the root mean square of the three magnitude data sets was calculated, minimizing effects from phase errors caused by eddy currents.

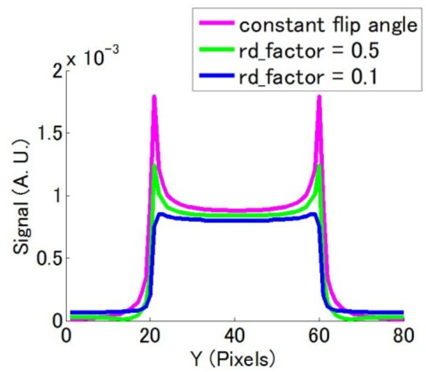

Fig. 2 Simulation results of image profiles of a rectangular subject with constant and variable flip angle trains.

Computer Simulation: The behavior of DP-bSSFP was calculated with one-dimensional simulations in the ky direction with constant and variable flip angle trains (rd_factor = 0.5, 0.1). We assumed that the subject had a rectangular profile with an $NiCl_2$ solution phantom characteristics (T1/T2 = 108 ms/ 96 ms, and ADC = 2.0 × 10^{-3} mm^2/s). Imaging parameters included: TR/TE = 4.6 ms/2.3 ms, matrix = 80, ETL = 40, α_{max} = 45 degrees, b = 500 s/mm^2, duration of diffusion preparation = 89 ms. We also assumed that T1 recovery was completed before the diffusion preparation.

Data Acquisition: We performed the DP-bSSFP scans with constant and variable (rd_factor = 0.5, 0.1) flip angle trains on GE 1.5 T HDxt MR imaging system (GE Healthcare, Waukesha, WI, USA) with an 8-channel cardiac array coil. We used an $NiCl_2$ solution phantom (T1/T2 = 108 ms/ 96 ms). ChemSat pulse was used for fat suppression between the diffusion preparation and bSSFP sequences. MPG pulses were applied on all the three axes simultaneously with b-values of 10 and 500 s/mm^2. Other imaging parameters included: TR/TE = 4.6 ms/2.3 ms, BW = ±125 kHz, FOV = 30 cm x 30 cm, slice thickness = 5.0 mm, matrix = 160 x 160, ETL = 40, α_{max} = 45 degrees, ASSET acceleration factor = 2, wait time between echo trains = 1 s, duration of diffusion preparation = 89 ms. Edge enhancement effects were evaluated using upstroke index (UI) defined by (P – H)/(P + H) where P is the peak intensity value at the anterior edge and H represents the average of the 30 pixels in the phantom center. [4] UI was calculated along the phase encoding direction.

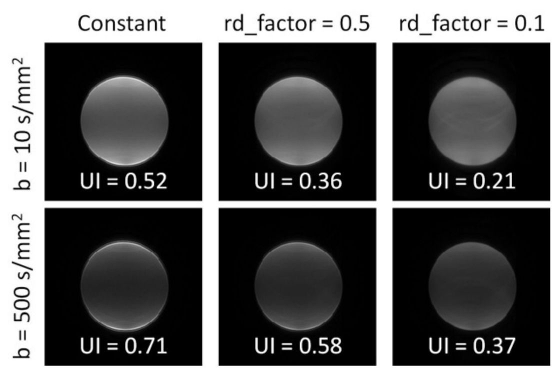

Fig. 3 Phantom images acquired with (left) constant flip angle, and variable flip angle of (middle) rd_factor 0.5 and (right) rd_factor 0.1. Upstroke index (UI) of each image is also shown

Results: In both simulation and phantom scan, variable flip angle reduced edge enhancement effect that was noticeable with constant flip angle (Figures 2 and 3). UI measured in phantom experiments decreased with the variable flip angle method, also showing edge enhancement reduction quantitatively. Rd_factor of 0.1 had lower UI than rd_factor of 0.5. The ADC values calculated with the two b-values (10 and 500) were same (0.0016 mm^2/s) among the three methods, which was lower than the value calculated from conventional DW-EPI (0.0020 mm^2/s).

Discussion: In this work, we demonstrated edge enhancement reduction by variable flip angle in 3D DP-bSSFP with centric view ordering, decreasing T1 recovery effect during data acquisition. This variable flip angle strategy can be applied to any other view orderings, such as sequential ordering, to correct for undesired effects of the T1 recovery. ADC discrepancy between DP-bSSFP and DW-EPI implied that T1 recovery between the period from diffusion preparation to data acquisition was not negligible. Optimization of the rd_factor for various organs is to be investigated in future studies.

Conclusion: We have demonstrated that variable flip angle corrected for signal modulation effects of T1 recovery in DP-bSSFP. This can lead to homogeneous 3D diffusion weighted image acquisition of subjects with short T1 recovery times.

References: 1. Jeong EK, Kim SE, Parker DL. High-resolution diffusion weighted 3D MRI, using diffusion weighted driven-equilibrium (DW-DE) and multishot segmented 3D-SSFP without navigator echoes. Magn Reson Med. 2003;50(4):821-829.

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