# High Resolution DTI using Dual-density Spiral for Efficient Sampling and Reduced Off-resonance Artifacts

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**Target Audience:** Researchers and clinicians interested in high resolution DWI or DTI

**Purpose:** Interleaved variable density spiral (VDS) [1] has been used to generate high resolution DTI with reduced distortion, using the densely oversampled region in k-space center to correct motion induced phase errors. The prolonged readout duration, however, can amplify the blurring artifacts of spiral sampling. Although the readout duration can be shortened by using more interleaves, the scan time will increase correspondingly. This study aims to reduce the blurring artifacts and increase the sampling efficiency of VDS DWI through modifying the trajectory design.

**Theory:** The conventional VDS trajectory is designed using an equation $k(\tau) = \lambda \tau^{\alpha} e^{j\omega\tau}$ [1,2], where $\alpha$ is a parameter controlling the change of sampling density in the radial direction. For each interleaf, the region around the central k-space will be oversampled and the sampling density will drop down gradually as the k-space traverses out (Fig. 1a). The VDS provides redundant information for interleaved DTI since only a certain full-sampled k-space (FSK) region is needed. In this study, a dual-density spiral (DDS) trajectory [3] is used instead, which can be expressed by the following equation,

$$\mathbf{k}(\varphi) = A k_r(\varphi) e^{j\varphi}, \text{ with } \frac{dk_r}{d\varphi} = \begin{cases} 1/N & \text{When } \varphi \le \varphi_1 \\ 1 + \dfrac{1-1/N}{\varphi_2 + \varphi_1}(\varphi_2 - \varphi_1) & \text{When } \varphi_1 < \varphi \le \varphi_2 \\ 1 & \text{When } \varphi \ge \varphi_2 \end{cases}$$

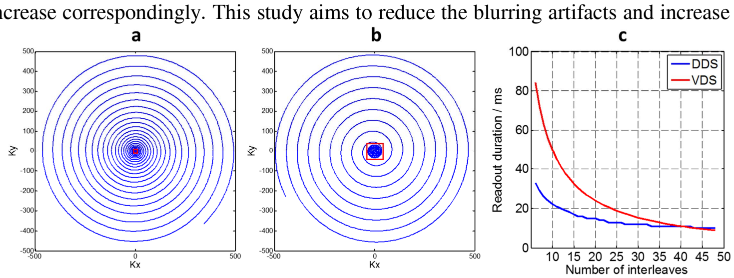


**Fig**.1. Trajectory plots of VDS (a) and DDS (b), where the red rectangle represents the FSK. (c) is the comparison of the readout duration at different numbers of interleaves (from 6 to 48), with the maximum gradient amplitude and slew rate of 40mT/m and 200 mT/m/s respectively and sampling matrix size=220×220. The size of FSK is fixed to 8×8 in DDS, while it will reduce from 8×8 to 2×2 gradually as the number of interleaves increase in VDS (α=4).

Here $k_r$ and $\varphi$ are the radius and phase of the k-space respectively. $N$ is the oversampling factor in the k-space center. The data will be oversampled $N$ times at the center k-space and normally sampled at the outer k-space (Fig. 1b). $\varphi \in (\varphi_1, \varphi_2]$ is the transition region between two different densities. Using DDS, one can acquire multi-shot DWI data with higher sampling efficiency than VDS with the same gradient performance (Fig. 1c), e.g., 12 interleaves can be used to achieve 20ms readout duration for DDS, while 28 interleaves are required for VDS; another advantage of DDS is that it can estimate motion-induced phase errors with higher resolution, since the size of FSK can be easily adjusted.

**Methods:** 1) Data acquisition: *In vivo* brain DTI data were acquired on healthy volunteers using a Philips 3T scanner and an 8-channel coil. The maximum gradient amplitude used is 40 mT/m and slew rate 200 mT/m/ms. Two DTI scans were performed using VDS and DDS respectively, both with 12 interleaves. In VDS, α was set to 4, which created a FSK of 8×8 for each interleaf with a readout duration of 30ms. In DDS, FSK was set to 16×16 to guarantee sufficient correction of motion-induced phase errors [4] and was actually under-sampled by a factor of 3 to further reduce the readout duration (18ms here). The imaging parameters included, b=1000s/mm$^2$, number of diffusion directions=6, TE/TR=54/2400ms, slice thickness=5mm, number of signal averages (NSA) =2, FOV=220×220mm$^2$, sampling matrix size=220×220. Single-shot EPI data with resolution of 2×2mm$^2$ were acquired as a reference, using SENSE factor=2 and TE/TR=93/2400ms (the other parameters were the same with spiral DTI). 2) Motion-corrupted data rejection: Those interleaves corrupted by severe motion were detected by measuring the k-space dispersion [5] of each interleaf (the threshold is set to 1.2) and rejected before reconstruction. 3) Phase correction: Both VDS and DDS DTI data were reconstructed using simultaneous phase correction and SENSE reconstruction [6]. Particularly, for DDS data, the under-sampled navigator in k-space center was firstly reconstructed using SENSE and then incorporated into the phase correction. 4) Off-resonance correction: The conjugate phase off-resonance correction method [7] was used to suppress the blurring artifacts of the reconstructed images. 5) FA map calculation: DtiStudio [8] was used to calculate the FA maps using the images after off-resonance correction.

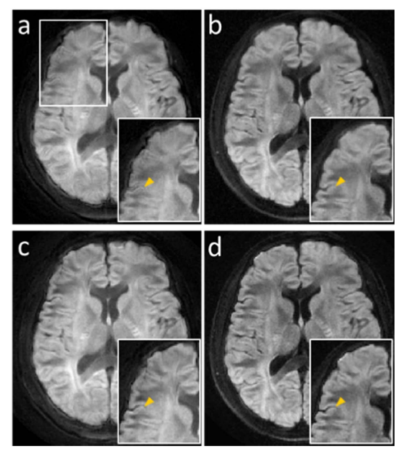


**Fig**.2. DW images with off-resonance correction from VDS (a) and DDS (b), and without correction from VDS (c) and DDS (d). Blurring artifacts are reduced in DDS (yellow arrows in the zoomed image).

**Results and Discussion:** The diffusion-weighted images with/without off-resonance correction from VDS and DDS were compared in Fig. 2. In both conditions, DDS has reduced blurring artifacts, which is due to the shorter readout duration than VDS. In Fig. 3, the images in regions of the brain stem with relatively severe CSF pulsation and thus largely nonlinear phase errors, were shown. Besides the reduced blurring, DDS has reduced signal loss and generates more accurate FA map, which is considered to be the contribution of more sufficient phase correction.

**Conclusion:** In this study, a dual-density spiral trajectory was proposed and implemented in high resolution DTI. *In vivo* results show the proposed method can reduce the off-resonance artifacts, improve sampling efficiency and correct motion-induced phase errors more accurately in comparison with the traditional variable density spiral DTI.

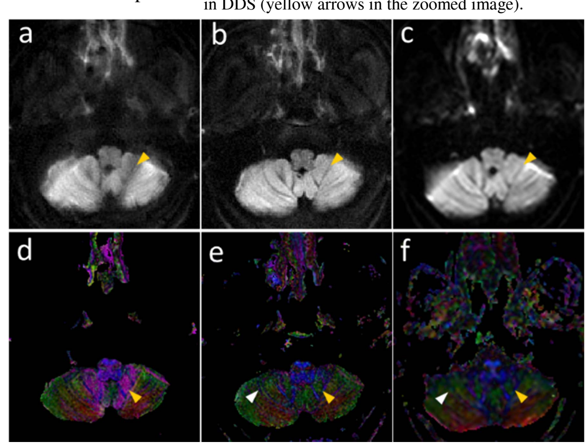


**Fig**.3. DW images (no off-resonance correction) from VDS (a), DDS (b) and single-shot EPI (c) and their FA maps (d)-(f). DDS has reduced blurring and signal loss (yellow arrows in the 1st row) and more accurate FA maps (yellow arrows in the 2nd row). Detailed structures in cerebellum can be observed more clearly from DDS than the single-shot EPI DTI (white arrows).

**References:** [1] Liu C et al., MRM 2004;52(6):1388-1396. [2] Kim DH et al., MRM 2003;50(1):214-219.
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