

# Improved angular resolution at low b-values in Diffusion Spectrum Imaging through Radial acquisition in q-space

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**Target audience** Scientists and clinicians interested in acquiring Diffusion Spectrum MRI at lower b-values.

**Purpose** To demonstrate that radial q-space sampling for Diffusion Spectrum MRI improves ODF sampling and angular resolution at lower b-values as demonstrated by computer simulations and in a clinical scanner *in vivo*.

Diffusion Spectrum MRI (DSI) [1] has been shown to non-invasively image the anatomical details of the microstructure of the brain, including complex distributions of intravoxel fiber orientations [2,3]. These properties depend on the model-independent determination of the Orientation Distribution Function (ODF) through the sampling of the ODF's Fourier transform in q-space [1]. When studying intravoxel fiber distributions, the angular resolution of the sampling method is crucial in accurately identifying fiber crossings [4]. In conventional DSI implementations, q-space is sampled on a rectangular grid and, consequently, the angular resolution is proportional to the inverse of the largest distance sampled in q-space. Hence, to increase the angular resolution, more shells have to be acquired, resulting in a cubic increase for the number of required samples and the acquisition time.

In the recently proposed Radial q-space sampling for q-space [5,6], the nominal angular resolution is primarily determined by the number of radial lines along which samples are acquired rather than by the number of shells. Hence, in theory, the angular resolution is independent of the number of shells (above a certain threshold). This results in improved DSI reconstructions at a lower number of shells, a lower number of q-space samples and at shorter acquisition times. An additional advantage of the radial q-space sampling is that it avoids interpolation errors introduced in rectangular sampling of q-space.

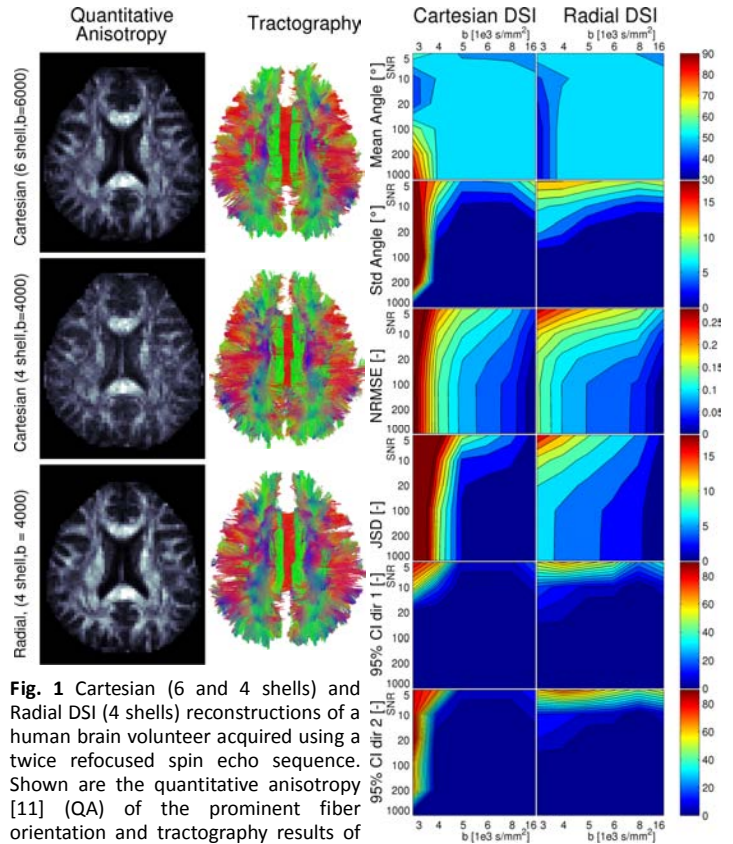
**Methods Experimental:** For both Cartesian (rectangular) and Radial q-space sampling schemes, *in vivo* brain data of a healthy volunteers were acquired during the same session using a twice-refocused spin echo sequence. The radial sampling scheme [5,6] acquires several q-space samples (= number of shells) along a number of radial lines (e.g. 59). This has the advantage that every radial line acquired in q-space is directly connected to a value of the radial ODF at the same angular location in the spatial domain by the Fourier slice theorem [5]. The DSI acquisitions were performed on a 3T scanner (Skyra, Siemens, Erlangen) using a 32-channel head coil ( $b_{max}=6000$  (cartesian)/4000 (radial), TR = 1500,  $2.3 \times 2.3 \times 5$  mm resolution, 10 slices, multiband acceleration of 2 [7], TE = 133ms(Cartesian)/114ms(radial)). The conventional rectangular sampling foresaw in 709 samples (6 shells, half sphere, 17:52min) and 257 samples (4 shells, half sphere, 6:29min). For the radial DSI q-space sampling, 236 samples were acquired arranged on 59 radial lines, evenly distributed on a radius 4 half sphere (6:01min). Reconstructions were performed offline using custom-made software (Matlab, Mathworks) and displayed using Matlab and DSI Studio [8].

**Simulations:** ODF's of two crossing fibers (angle  $60^\circ$ ) and a water pool (10%) were also simulated as measured with radial (59 radial lines x number of shells) and rectangular (half sphere, number of shells = b-value/1000) sampling and Rician noise added to the data. The simulation results were compared using the normalized RMSE (NRMSE) and the Jensen-Shannon Divergence (JSD) [9] of the Orientation Distribution Functions (ODFs) relative to the ODF's of the mean of the highest b-value simulation. confidence intervals [10] were calculated at each SNR and b-value.

**Results and Discussion** Figure 1 compares *in vivo* DSI reconstructions using rectangular and radial q-space sampling. The quantitative anisotropy [11] maps and tractography results demonstrate that the low b-value Radial sampling outperforms the low b-value Cartesian sampling. This observation is also reproduced in the simulation results (Figure 2), which show larger deviations from the simulated ODF as the number of shells drops in Cartesian sampling in comparison to Radial sampling. The simulation results also illustrate the effects of interpolation errors in the conventional Cartesian DSI (Figure 3) as "false" peaks appear in the ODF when the b-value and/or SNR are low. In this setting, the radial DSI approach clearly outperforms its Cartesian counterpart.

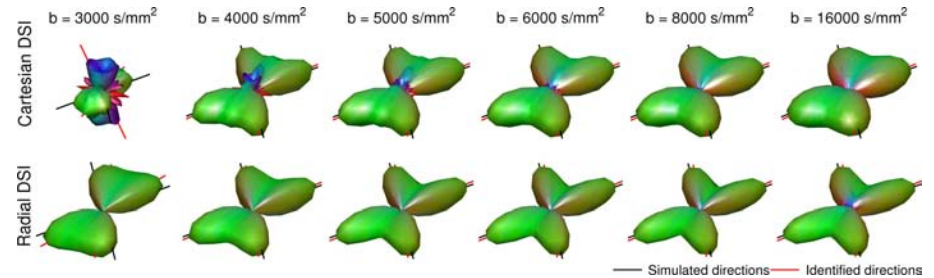
**Conclusion** Radial q-space sampling for DSI is shown to have an improved angular resolution at lower b-values compared to rectangular q-space sampling for a similar number of samples. These findings, combined with earlier published results [5,6], showing the independence of angular resolution of q-space radius and the avoidance of interpolation errors present when using conventional rectangular q-space sampling, suggest that radial acquisition of q-space can be favorable for DSI.

**Funding** NIH 2R01CA111996-06A1. **References** [1] Callaghan P., Principles of Nuclear Magnetic Resonance Microscopy, Oxf. Univ. Press, 1994. [2] Wedeen VJ, et al., Science, 335:1628,2012. [3] Fernandez-Miranda JC, et al., Neurosurg., 71:430, 2012. [4] Wedeen VJ, et al., MRM 54:1377, 2005. [5] Boada FE, et al., Proc ISMRM, p3177, 2013. [6] Baete S, et al., ISMRM Diffusion Workshop, p40, 2013. [7] Setsompop K, et al., 63:569, 2012. [8] Yeh FC, et al., IEEE TMI 29:1626, 2010. [9] Cohen-Adad, et al., JMRI 33:1194-1208, 2011. [10] Jones DK, et al. MRM 51:807-15, 2004. [11] Yeh FC, et al., IEEE TMI 54:1377-1386, 2005.



**Fig. 1** Cartesian (6 and 4 shells) and Radial DSI (4 shells) reconstructions of a human brain volunteer acquired using a twice refocused spin echo sequence. Shown are the quantitative anisotropy [11] (QA) of the prominent fiber orientation and tractography results of the central 10 slices.

**Fig. 2** Comparisons of reconstruction parameters of simulations of Cartesian and Radial DSI reconstructions of two crossing fibers (angle  $60^\circ$ ) at different b-values ( $\#shells = b\text{-values}/1000$ ) and SNR levels. Compared parameters are the mean and standard deviation of the measured angle between the identified crossing fibers, the mean normalized RMSE error (NRMSE) and the mean Jensen-Shannon divergence [9] (JSD) of the ODFs relative to the highest b-value simulation, and the 95% confidence intervals (CI) [10] of the identified first and second fiber directions.



**Fig. 3** Simulated ODF's of two crossing fibers (angle  $60^\circ$ ) sampled with Cartesian and Radial q-space sampling at several b-values ( $\#shells = b\text{-values}/1000$ ). With rectangular q-space sampling extra peaks appear at lower b-values due to interpolation errors, whilst with radial q-space sampling all directions are still correctly identified.