

# Projection Distribution of 3D UTE Sequences for Sodium MRI with Anisotropic Resolution and Uniform Sampling

Simon Konstantin<sup>1</sup>, Philipp Krämer<sup>1</sup>, and Lothar R. Schad<sup>1</sup>

<sup>1</sup>Computer Assisted Clinical Medicine, Heidelberg University, Mannheim, Germany

## Purpose:

Sodium MRI acts as biomarker for tissue viability and has been applied to many human organs/diseases [1]. SNR-efficient sequences with short echo times are required for imaging of spin-1/2 nuclei. Established ultra-short echo time (UTE) sequences are 3D radial techniques with density adaption [2] and twisted projection imaging (TPI) [3]. However, so far no UTE sampling strategy exists for anisotropic resolution with uniform k-space sampling for highest SNR efficiency. In this study, projections are distributed on rings so that uniform sampling and optimal SNR efficiency is achieved for UTE imaging with anisotropic resolution.

## Theory:

While the angular distances  $\Delta\theta$  of adjacent rings are the same for spherical surfaces (Fig. 1a), their distances must be adapted for anisotropic resolutions dependent on the anisotropy factor  $c$  (i.e., ratio between z-resolution and in-plane resolution) that leads to varying sampling densities of trajectories on different rings (Fig. 1b). For optimal SNR efficiency, the number of projections on different rings must be corrected with a weighting factor  $W(\theta)$  to achieve a homogeneous noise distribution in k-space. This weighting factor is proportional to the area of the triangle (red in Fig. 1c), which is proportional to its base  $b$  and height  $h$ . The base is in good approximation the distance of adjacent rings that is constant and the height is the projection of  $k_z$  on the normal line at its ending point on the ellipse. Thus, the weighting factor can be estimated as

$$W(\theta_i) = k_i \cos(\gamma_i) / k_{N_0} \quad (1)$$

with  $k_i$  the distance between the corresponding ring to the k-space center ( $k_{N_0}$  for the last ring that is nearest to the pole) and  $\gamma_i = \arctan(c^2 \cdot \cot\theta_i) + \theta_i - \pi/2$  the angle between  $k_i$  and the height  $h_i$  of the corresponding triangle.

## Methods:

Measurements were performed on a 3 T whole-body MR scanner (Magnetom TIM Trio, Siemens Healthcare, Erlangen, Germany). A double-tuned birdcage head coil (Rapid Biomedical, Rimpf, Germany) was employed for phantom measurements. For imaging of the intervertebral disks, a transmit coil consisting of a fixed upper and lower part with one sodium transmit channel was used. Signal was received using a flexible coil array with two sodium receive channels. A conventional projection reconstruction (PR) technique with constant readout gradient amplitudes and two different UTE acquisition schemes with density adaption in case of isotropic resolution (DAPR [2], TPI [3]) were investigated. Raw data were precompensated using the voronoi cell volumes of the k-space data points [4]. For the regridding procedure a convolution with a Kaiser-Bessel kernel was used. Voronoi cells associated with every k-space data point were used for calculation of SNR efficiency

$$\eta = \sqrt{V_{\text{mean}}^2 / \sum V_i^2} \quad (2)$$

The more the volumes  $V_i$  of these cells differ from the average volume  $V_{\text{mean}}$ , the less uniform the noise is distributed in k-space resulting in a loss in image quality. **Sequence parameters** were set as follows: TR=20 ms, TE=0.15 ms, FA=46° (global RF excitation), number of projections=21,000 and two averages resulting in a total measurement time of 14 minutes. A short readout duration ( $T_{RO}$ ) of 12.5 ms compared to  $T_2^* \approx 54$  ms of the phantom was used to reduce relaxation effects during data acquisition. A nominal in-plane resolution of  $\Delta x = 2.5 \times 2.5 \text{ mm}^2$  and an anisotropy factor  $c=4$  (i.e.,  $\Delta z=10 \text{ mm}$ ) were used. Same parameters were applied for imaging of intervertebral disks, but TE=0.45 ms, number of projections=15,000 resulting in a total measurement time of 10 minutes.

## Results:

The numbers of projections needed to fulfill the Nyquist criterion are depicted in Figure 2a in dependence of the anisotropy factor. The number of Nyquist projections is reduced for TPI compared to DAPR without twisting trajectories. The measurement time can be reduced for DAPR and TPI using higher anisotropy factors. The number of Nyquist projections is nearly independent of the anisotropy factor if projection distribution is adapted for uniform sampling (US), but much smaller than obtained by simple scaling of one gradient for anisotropic resolution. SNR efficiency (Fig. 2b) decreases with higher anisotropy factors due to varying areas of the different triangles (cf. Fig. 1c). However, SNR can be optimized from 81% (DAPR/ TPI) up to 98% (DAPR/ TPI-US), if the numbers of projections on each ring are weighted with  $W(\theta)$ . Image quality is much worse for PR with constant gradients (61%). Phantom simulations and measurements were performed to confirm the SNR results obtained by means of voronoi cells (cf. Fig. 2b). The relative SNR values from the measurements agree very well with those obtained by simulations (Table 1). Measurements of intervertebral disks were performed to confirm the SNR improvement under *in vivo* conditions. A SNR comparison of the TPI-US (Fig. 3) to the TPI sequence reveals an advantage of about 13%, which confirms the SNR ratio from the phantom simulations/ measurements (cf. Table 1).

## Summary and Conclusion:

Density-adapted acquisition schemes with anisotropic resolution were investigated with respect to SNR efficiency and measurement time. A weighting factor was derived for redistribution of projections on different rings in k-space to achieve uniform sampling with optimal SNR efficiency if no postfiltering is required.

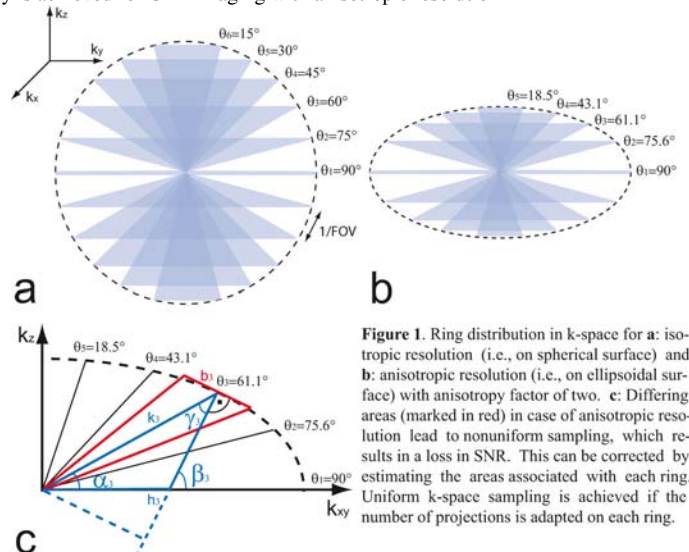
## References:

[1] Boada et al. Curr Top Dev Biol (2005) 70:77-101

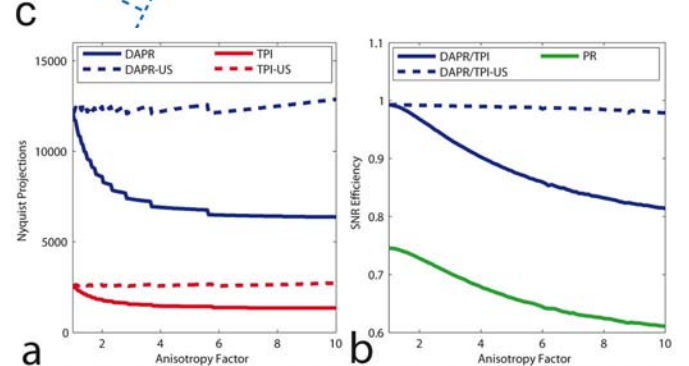
[2] Nagel et al. MRM (2009) 62:1565-73

[3] Boada et al. MRM (1997) 37:706-15

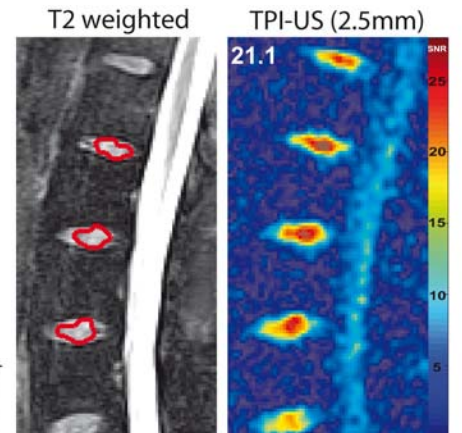
[4] Rycroft. Chaos (2009) 19:041111



**Figure 1.** Ring distribution in k-space for a: isotropic resolution (i.e., on spherical surface) and b: anisotropic resolution (i.e., on ellipsoidal surface) with anisotropy factor of two. c: Differing areas (marked in red) in case of anisotropic resolution lead to nonuniform sampling, which results in a loss in SNR. This can be corrected by estimating the areas associated with each ring. Uniform k-space sampling is achieved if the number of projections is adapted on each ring.



**Figure 2.** a: Number of projections needed to fulfill the Nyquist criterion and b: SNR efficiency in dependence of the anisotropy factor. The number of Nyquist projections is reduced by factor  $p$  for TPI compared to DAPR. More projections are needed for uniform sampling (US). The TPI and DAPR sequences possess the same SNR behavior because of identical radial evolution in k-space. Nearly optimal efficiency is achieved with the projection adapted techniques (US), while less SNR is expected with the uncorrected sequences (81%) and conventional PR (61%).



**Figure 3.** T2-weighted proton (left) and sodium (right) image of a healthy volunteer's intervertebral disks at nominal resolution of  $2.5 \times 2.5 \times 10 \text{ mm}^3$ . A SNR value of 21.1 was achieved in intervertebral disks (red ROIs). Zero-filling of factor 2 was applied.

**Table 1.** Relative SNR values at an anisotropy factor of four obtained by the voronoi method, phantom simulation and measurement. SNR values normalized to 1 for DAPR-US.

Relative SNR by Method	DAPR	DAPR-US	TPI	TPI-US	PR
Voronoi	0.91	1	0.90	0.99	0.69
Simulation	0.90	1	0.92	0.99	0.71
Measurement	0.93	1	0.91	1.01	0.68