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# Sodium magnetic resonance imaging using ultra-short echo time sequences with anisotropic resolution and uniform k-space sampling

Simon Konstandin [a,b,*,1], Philipp Krämer [a], Matthias Günther [b,c], Lothar R. Schad [a]

[a] Computer Assisted Clinical Medicine, Medical Faculty Mannheim, Heidelberg University, Theodor-Kutzer-Ufer 1-3, 68167 Mannheim, Germany
[b] MR-Imaging and Spectroscopy, Faculty 01 (Physics/Electrical Engineering), University of Bremen, NW 1 Otto-Hahn-Allee 1, 28359 Bremen, Germany
[c] Fraunhofer MEVIS, Universitätsallee 29, 28359 Bremen, Germany

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ABSTRACT

A method for uniform k-space sampling of 3D ultra-short echo time (UTE) techniques with anisotropic resolution in one direction is introduced to increase signal-to-noise ratio (SNR). State-of-the-art acquisition schemes for sodium MRI with radial (projection reconstruction) and twisting (twisted projection imaging (TPI)) trajectories are investigated regarding SNR efficiency, blurring behavior under $T_2^*$ decay, and measurement time in case of anisotropic field-of-view and resolution. 3D radial and twisting trajectories are redistributed in k-space for UTE sodium MRI with homogeneous noise distribution and optimal SNR efficiency, if $T_2^*$ decay can be neglected. Simulations based on Voronoi tessellations and phantom simulations/measurements were performed to calculate SNR efficiency. Point-spread functions were simulated to demonstrate the influence of $T_2^*$ decay on SNR and resolution. Phantom simulations/measurements and *in vivo* measurements confirm the SNR gain obtained by simulations based on Voronoi cells. An increase in SNR of up to 21% at an anisotropy factor of 10 could be theoretically achieved by TPI with projection adaption compared to the same sequence but without redistribution of projections in k-space. Sodium MRI with anisotropic resolution and uniform k-space sampling is demonstrated by *in vivo* measurements of human intervertebral disks and heart at 3 T. The SNR gain can be invested in a measurement time reduction of up to 32%, which is important especially for sodium MRI.



## 1. Introduction

The sodium ($^{23}Na$) and potassium ($^{39}K$) exchange between the intracellular and extracellular space plays an important role in living tissue [1]. The supply with energy in the form of adenosine triphosphate (ATP) and its hydrolysis cause the sodium–potassium pump ($Na^+$-$K^+$-ATPase) to maintain $Na^+$ and $K^+$ concentration gradients across the cell membrane. This ion exchange against the electrochemical gradient is essential to protect the cell from swelling/bursting and to function as a signal transducer. An intracellular sodium concentration of 12–20 mM and an extracellular concentration of about 145 mM are maintained in living tissue [2]. An ATP deficiency leads to a breakdown of the pump mechanism, which results in an increase in intracellular sodium concentration. Sodium MRI acts as biomarker for tissue viability and has been applied to many organs/diseases [3–10].

Sodium imaging suffers from low signal-to-noise ratio (SNR) because of a lower gyromagnetic ratio (11.26 MHz/T) and abundance of sodium nuclei in the human body (80 mM [11]) compared to protons (42.58 MHz/T and ≈ 88 M [11]). Furthermore, biexponential signal decay with short $T_2^*$ values of about 0.5–5 ms and 15–30 ms [12] for the fast and slow component in biological tissues places high demands on the acquisition technique. SNR-efficient sequences with short echo times and imaging of large voxel sizes are required to compensate for these drawbacks. Established ultra-short echo time (UTE) sequences for $^{23}Na$-MRI are 3D radial [13] techniques with density adaption [14] and twisted projection imaging (TPI) [15] with different sequence properties [16]. There are many k-space sampling schemes [17] that can be used, but so far no sampling strategy with anisotropic resolution and 3D center-out k-space trajectories exists for uniform sampling and highest SNR efficiency.

Applications such as imaging of cartilage [18,19], myocardium [20], multiple sclerosis [21,22] and Alzheimer's disease [23] recently came into the focus of sodium MRI. Although anisotropic resolutions are preferred when the anisotropic resolution is well aligned with the tissue anisotropy, most of the studies were performed with low isotropic resolution. Anisotropic resolution is recommended for sodium heart imaging in short-axis view to avoid partial volume

* Corresponding author at: MR-Imaging and Spectroscopy, Faculty 01 (Physics/Electrical Engineering), University of Bremen. Tel.: +49 421 218 59294; fax: +49 421 218 98 59294.
*E-mail address:* simon.konstandin@mevis.fraunhofer.de (S. Konstandin).
[1] Postal Address: Fraunhofer MEVIS, Universitätsallee 29, 28359 Bremen, Germany.

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effects (i.e., blood signal blurred into the myocardium) obtained by isotropic imaging with lower in-plane resolution, which hampers sodium quantification. The simplest solution for imaging with anisotropic resolution and short echo times is the use of 2D radial sequences [24]. Although variable-rate selective excitation can shorten the echo time [25], 3D sequences are preferred for covering the entire subject with shortest possible echo time. Anisotropic resolution with acquisition-weighted stack of spirals [26] and 3D center-out trajectories based on cones [27] and TPI [28] were recently applied. The simplest solution for anisotropic resolution is the scaling of the gradient along the desired direction of anisotropy (i.e. "pressing" the k-space sphere to an ellipsoid, in which data are acquired). However, k-space is not sampled uniformly anymore, the in-plane field-of-view (FOV) cannot be chosen independently from that along the direction of anisotropy, and the number of projections to fulfill the Nyquist criterion is not reduced. Thus, the aim of this study is to distribute projections in k-space for anisotropic resolution with uniform k-space sampling and minimal number of Nyquist projections. Furthermore, an acquisition technique based on twisting radial lines [29] (TWIRL) is presented for 3D sodium MRI that allows for very short measurement times. Imaging of the human heart and intervertebral disks is performed to confirm the SNR gain obtained by simulations and phantom measurements under *in vivo* conditions.

## 2. Theory

Different acquisition techniques were implemented and developed to obtain anisotropic resolution. These sequences are investigated regarding SNR efficiency, blurring behavior under the influence of $T_2^*$ decay, gradient hardware requirements, and the number of projections to fulfill the Nyquist criterion. The nominal in-plane resolution is $\Delta x = 1/(2k_{xy}^{max})$ and the resolution in z-direction $\Delta z = c \cdot \Delta x$ is scaled with an anisotropy factor $c > 1$. Here, the z-direction is defined as the direction of anisotropy and can be placed along any direction by rotating the reference system of the gradients.

### 2.1. Acquisition schemes

A conventional projection reconstruction (PR) technique with constant readout gradient amplitudes, an acquisition scheme with density adaption in case of isotropic resolution (TPI) and a stack of twisting radial lines (3D-TWIRLS) were developed and investigated for anisotropic resolution. To achieve the 3D-TWIRLS sequence, the 2D readout with twisting radial lines [29] was extended to a 3D sequence by applying fast phase encoding in z-direction. Non-selective RF excitation pulses and gradient and RF spoiling were used in all sequences.

### 2.2. Projection distribution

The polar and azimuth angle can be calculated [13] for a homogenous distribution of projections on a k-space sphere (i.e., isotropic resolution). However, this approach cannot be applied for homogenous sampling of k-space data acquired within an ellipsoid (i.e., anisotropic resolution) and the FOV in z-direction cannot be chosen differently from that in the xy-plane. Thus, the distribution of the endpoints of the trajectory is performed by dividing the k-space in $N_\theta$ rings for PR and TPI (Fig. 1a left/middle). In case of anisotropic resolution or FOV, the angular distance $\Delta\theta$ of adjacent rings on the ellipsoidal surface is not equidistant anymore as it is for a sphere (cf. Fig. 2a, b) and must be calculated numerically for the desired $FOV_z$ in z-direction to fulfill the Nyquist criterion $\Delta k = 1/FOV_z$. The projections on each ring are distributed with constant angular distance $\Delta\phi = 2\pi/N_\phi(\theta)$, whereas the number of projections on a ring with azimuth angle $\theta$ is proportional to the respective ring circumference

$$N_\phi(\theta) \propto \frac{\sin\theta}{\sqrt{1-\varepsilon^2 \sin^2\theta}} \tag{1}$$

with eccentricity $\varepsilon = \sqrt{1-1/c^2}$ and anisotropy factor $c$.

The 3D-TWIRLS sequence uses phase encoding (i.e., Cartesian sampling) in z-direction and in-plane frequency encoding with same projection distribution on each ring as mentioned before (Fig. 1a right). The in-plane resolution and FOV can be chosen independently from those in z-direction. A short blip gradient is applied between global RF excitation and data acquisition for phase encoding with minimal signal loss caused by $T_2^*$ decay.

### 2.3. Projection adaption for uniform sampling

While the angular distances $\Delta\theta$ of adjacent rings are the same in case of isotropic resolution (Fig. 2a), their distances must be adapted for anisotropic resolutions dependent on the desired $FOV_z$ in the z-direction and anisotropy factor $c$ (Fig. 2b). This leads to varying sampling densities of trajectories with endpoints on different rings. For a homogeneous noise distribution in k-space (i.e., optimal SNR efficiency [30]), these different sampling densities must be considered by adapting the number of projections on different rings. A factor $W(\theta)$ proportional to the area of the triangle (marked in red in Fig. 2c), which is proportional to its base (b) and height (h), is derived. The base can be approximated by the distance of the neighboring rings, which was chosen to be constant for all rings dependent on $FOV_z$. The distance from the k-space center to the *i*-th ring is defined as $k_i$ and the height is the projection of $k_i$ on the normal line at its endpoint on the ellipse. Thus, the factor $W(\theta)$ can be estimated as:

$$W(\theta_i) \propto k_i \cos(\gamma_i) \tag{2}$$

with

$$k_i = \frac{k_1}{\sqrt{c^2 \cos^2\theta_i + \sin^2\theta_i}}$$
$$\gamma_i = \beta_i - \alpha_i = \arctan\left(c^2 \tan\alpha_i\right) - \alpha_i = \arctan\left(c^2 \cot\theta_i\right) + \theta_i - \pi/2 \tag{3}$$

where the relationship

$$\tan\alpha_i = \left(1-\varepsilon^2\right)\tan\beta_i \tag{4}$$

between polar and normal angle was used.

The projection adaption for uniform k-space sampling leads to a higher number of projections needed to fulfill the Nyquist criterion. Because of the largest area near the equator and the smallest one near the pole, the number of projections must be increasingly scaled up to factor $c$ toward the equator (cf. Eq. (2)). The number of projections $N_{Nyq}$

$$N_{Nyq} = \sum_i W(\theta_i) \cdot \pi \frac{FOV_x}{\Delta x} \cdot \frac{k_i \sin\theta_i}{k_1} \approx \sum_i \pi \frac{FOV_x}{\Delta x} \cdot \frac{c \sin\theta_i \cos\gamma_i}{c^2\cos^2\theta_i + \sin^2\theta_i} \tag{5}$$

is dependent on the factor

$$W(\theta_i) = \frac{k_i \cos(\gamma_i)}{k_{N_\theta}} \tag{6}$$

the in-plane $FOV_x$ and resolution $\Delta x$, the anisotropy factor $c$ of the ellipsoid, and the ring positions $\theta_i$ determined by the $FOV_z$ in z-