SNR-Efficient Anisotropic 3D Ultra-Short Echo Time Sequence for Sodium MRI with Retrospective Gating

Simon Konstandin[1] and Matthias Günther[1,2]

[1]MR-Imaging and Spectroscopy, Faculty 01 (Physics/Electrical Engineering), University of Bremen, Bremen, Germany, [2]Fraunhofer MEVIS, Bremen, Germany

Purpose:

Sodium MRI is subject of increasing interest since it gives additional information on tissue viability and cell processes.[1] Most studies are performed using 3D ultra-short echo time (UTE) sequences with isotropic resolution. However, for some applications such as cartilage or heart imaging, anisotropic resolution is preferred to reduce partial-volume effects that hamper sodium quantification. Recently, a 3D acquisition scheme was presented to achieve optimal SNR efficiency for UTE imaging with anisotropic resolution.[2] Furthermore, it could be shown that retrospective electrocardiogram (ECG) gating with golden angle increments improves SNR because of changing heart rate and arrhythmia.[3-5] The aim of this study is to combine these two optimizations, i.e. to find an approach for uniform k-space sampling in case of 3D anisotropic resolution and sliding window reconstruction.

Theory:

In case of 3D radial imaging with isotropic resolution, k-space data have to be acquired within a sphere. It could be demonstrated that a projection distribution using multidimensional golden means leads to a more uniform sampling, i.e. higher SNR and fewer artifacts, for dynamic MRI at various temporal resolutions.[5] In case of anisotropic resolution, however, no analytical formula could be found for the azimuth angle to acquire k-space uniformly on an ellipsoidal surface. In this study, a method is presented to determine the projection distribution on many virtually placed rings to achieve an azimuthal angle distribution according to the golden ratio (GR) with high k-space homogeneity. In analogy to the angle distribution for 2D radial imaging (cf. Figure 1a), where the circumference is used for the GR $\gamma^{1D}\approx 0.618$, the sum of the circumferences of many virtually placed rings is employed to apply the GR $\gamma_2^{2D}\approx 0.618$ for 3D UTE imaging with anisotropic resolution (cf. Figure 1b). By this, projections can be homogeneously distributed on the ellipsoidal surface, but for uniform k-space sampling the circumferences must be multiplied with a correction factor recently derived.[2]

Methods:

Simulations were performed using Matlab (The Mathworks Inc., Natick, MA) and density-adapted radial trajectories[4] for 2D imaging, while twisted projection imaging[6] was used for 3D UTE imaging to shorten simulation/measurement time compared to radial projections. Acquisition parameters were: 2.5×2.5 mm^2 ($\times$10 mm) nominal resolution (2D/3D), 200 mm field-of-view, and k-space fractions where density adaption starts of 0.14 and 0.34 leading to a SNR efficiency of about 0.99 and 0.97 (2D/3D), respectively, if projections are homogenously distributed. Instead of using the volumes V_i of the Voronoi cells[2] for calculation of SNR efficiencies η, k-space homogeneity was investigated using the weighting matrix $D(\boldsymbol{k})$ (also used for postcompensation after gridding) and calculated as follows:

$$\eta = \sqrt{N\cdot\bar{V}^2 \Big/ \sum_i V_i^2} = \sqrt{\left(\sum_{\boldsymbol{k}} 1/D(\boldsymbol{k})\right)^2 \Big/ N\sum_{\boldsymbol{k}} 1/D^2(\boldsymbol{k})} \qquad (1)$$

where $\bar{V}$ is the mean volume of all N Voronoi cells V_i and $D(\boldsymbol{k})$ is the k-space density obtained by the weighting matrix after gridding with a Kaiser-Bessel kernel with window width of 5.0 (β=7.43, without oversampling[7]).

Results & Discussion:

SNR efficiency of the density-adapted 2D radial sequence was calculated for equally spaced projections and projections distributed according to the golden angle of 222.5° (cf. Figure 2a) using the weighting matrix (cf. Figures 2b-d). As already shown analytically by Winkelmann et al.[3], maximum SNR is achieved if the number of projections is equal to a Fibonacci number and lower between.

For 3D imaging, the presented method for homogeneous distribution of projections on an ellipsoidal surface was applied (cf. Figure 1). A random heartbeat of 60-70 min^{-1} was simulated and projections in the entire diastole of ≈723 ms (cf. Figure 3a, red) and in a window of 200 ms (cf. Figure 3b, red) were used for reconstruction. Since k-space is not sampled uniformly if projections are homogeneously distributed on the ellipsoidal surface, the weighting of the different rings was corrected as recently shown[2] leading to higher SNR efficiencies (green curves). First phantom simulations (not shown) confirm this SNR gain but have to be compared with real measurements in the near future.

Conclusion:

In this work, a 3D acquisition scheme based on the golden ratio was presented to achieve high SNR efficiency for UTE imaging with anisotropic resolution and retrospective ECG gating. This SNR gain can be invested in higher resolutions and/or measurement time, which is important for sodium MRI.

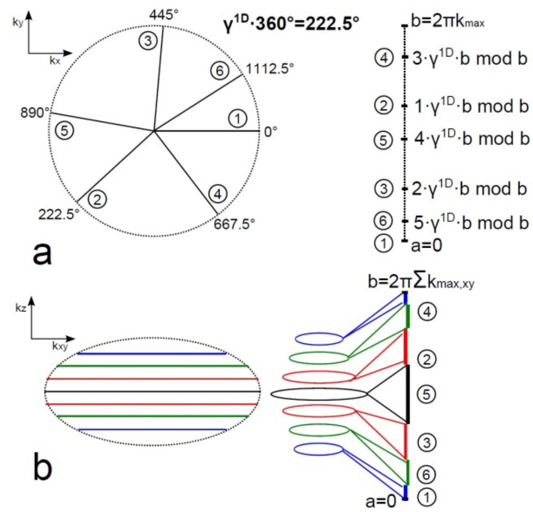

Figure 1: *Projection distribution according to the golden ratio. a) For the 2D case, this corresponds to an angle of $\gamma^{1D}\cdot 360°=222.5°$. b) For the 3D case with anisotropic resolution, the polar angle is distributed according to γ_1^{2D}. The azimuth angle is determined by virtual placing of many rings and projection weighting on these rings according to their circumferences using the GR of γ_2^{2D}.*

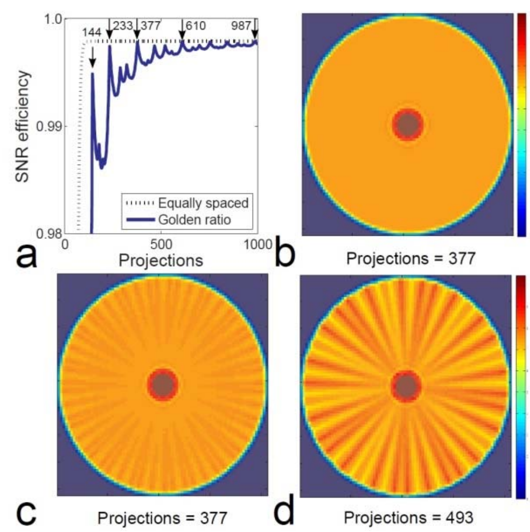

Figure 2: *Comparison between equally spaced projections and distribution according to the GR using a 2D density-adapted radial scheme. a) SNR efficiency obtained by the weighting matrix (b-d) used for postcompensation. Maximum SNR efficiency can be observed for equally spaced projections (b) and if the number of projections is equal to a Fibonacci number (arrows,c), while the SNR is lower between two Fibonacci numbers using the GR (d).*

References:

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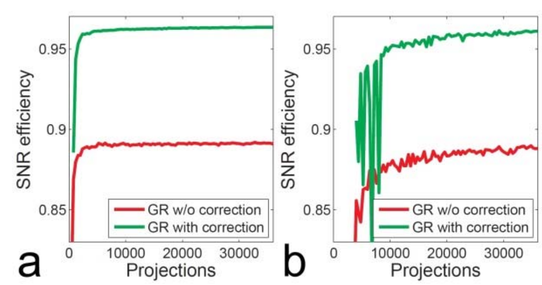

Figure 3: *Comparison of SNR efficiency between 3D projections distributed according to the method shown in Figure 1 without (red) and with (green) correction for uniform k-space sampling. a) All projections in the diastole (≈ 723 ms at mean heartbeat of 65 min^{-1}) were retrospectively chosen. b) Projections only in a sliding window of 200 ms duration were considered for calculation.*