MR-Encephalography using a Spherical Stack of Spirals Trajectory

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Introduction: Recent work has explored the possibilities of full brain 3D-imaging at a temporal frequency of 10Hz [1,2,3] to allow filtering of physiological noise and for monitoring fast functional activation. The short acquisition time is achieved by using highly undersampled trajectories, combined with multi-coil arrays and a regularized reconstruction. Good results have been obtained with concentric shells [4], which have the property to exploit the maximum slew rate of the gradient system. Their disadvantage though is, that off-resonance leads to blurring and signal dropout rather than distortion as in echo planar imaging (EPI). This is due to the slow encoding direction being none of the reciprocal coordinates k_x, k_y, k_z, but rather the radial direction in k-space. We propose a spherical stack of spirals (SoS) trajectory [5] for better off-resonance characteristics while still exploiting the maximum slew rate of the system.

Trajectory: A single spiral and the Nyquist constraint are given by

$$k(t) = r(t)e^{i\vartheta(t)} \quad \text{and} \quad \frac{dr}{d\vartheta} = \frac{R(k)}{2\pi \cdot FOV},$$

where r and ϑ are polar coordinates and $R_r(k) = R_{r,\min} + \Delta R_r |k|$ the reduction factor. From there two differential equations $G_{\max} = f(r, \dot{r}, \vartheta)$ and $S_{\max} \cdot e^{-\gamma r} = g(r, \dot{r}, \ddot{r}, \vartheta)$ can be derived, where $G_{\max}$ and $S_{\max}$ are the maximum gradient strength and slew rate of the system. The slew rate is scaled by the empirical factor $\gamma = 0.2m$ to reduce peripheral nerve stimulation. With those two equations, spirals can be calculated analytically, ensuring an efficient k-space sampling. The distance $\Delta k_z \propto |k_z|$ between two spirals produces a linear varying reduction factor R_z. Varying the radius of the spirals creates a spherical k-space surface. The spirals are smoothly connected to obtain a single shot trajectory.

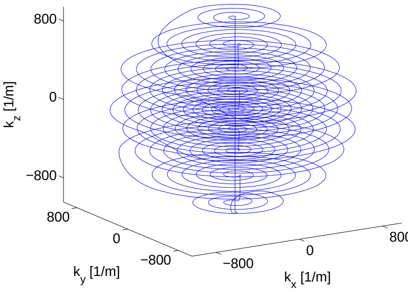

Figure 1: Spherical stack of spirals

Image Reconstruction: Image reconstruction was performed offline. The signal equation is in matrix form $S = Ax$, with the measured signal S, the forward operator A, including the trajectory and coil sensitivities. The image x is found by using a non-linear conjugate gradient to minimize the cost function $f(x) = \|Ax - S\|_2^2 + \lambda \|TV \cdot x\|_1$, where λ is the regularization parameter and TV the total variation operator [6, 7].

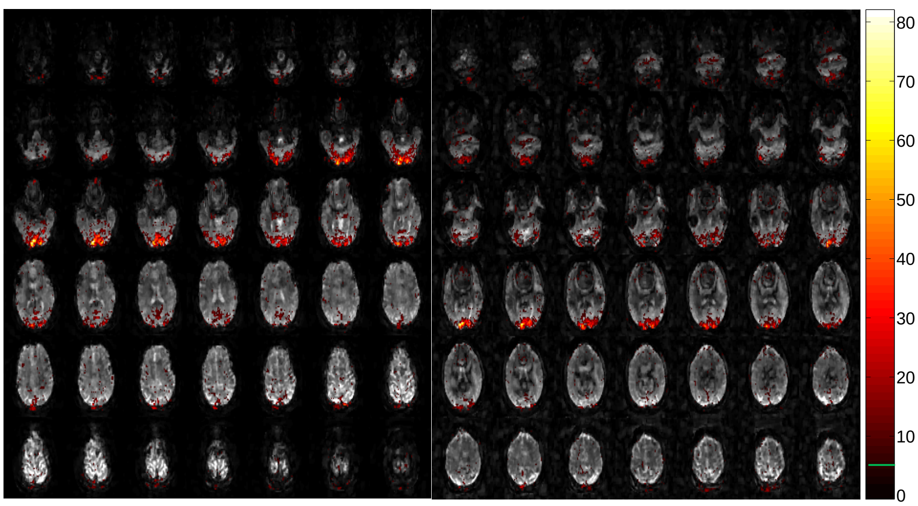

Figure 2: Overlays of t-maps and the first frames. Left/right: z-gradient blips are positive/negative during read out. The images are distorted in the opposite directions. In areas of strong off-resonance gradients, the images show completely different behavior.

Methods: Experiments were performed on a 3T TIM TRIO scanner (Siemens, Erlangen, Germany) using a 32 channel head coil array for signal reception. Coil sensitivities and an off-resonance map (ω-map) were derived from a 2D multi-slice, multi gradient echo image (TR = 1s, TE_1/TE_2 = (2.46/4.92)ms). For the functional scan a spoiled gradient echo sequence with a SoS trajectory was used. The reduction factors were $R_{r,\min} = \Delta R_r = \Delta R_z = 3$, $R_{z,\min} = 2$, FOV = $(0.192\text{m})^3$, Res = $(3\text{mm})^3$, T_{AQU} = 75ms, TE = 37ms, TR = 100ms, dwell time = 5µs. The experiment was repeated with the trajectory flipped in z-direction and the same parameters in other respects. Visual stimulation was performed by presenting 15s flickering checkerboard, followed by 15s rest, repeated three times. Activation maps where computed using SPM8 (www.fil.ion.ucl.ac.uk/spm).

To visualize the different off-resonance behavior by flipping the trajectory in z-direction, an 1D simulation was performed. From the in vivo ω-map one column (head >> foot) was taken, passing through the sinus-frontalis, where the worst off-resonance is found. Constant, full sampling over 75ms was assumed. As a forward operator a Fourier matrix, multiplied with the field inhomogeneity, was taken. Reconstruction was done by an inverse Fourier transformation.

Results: The MREG reconstructions in Figure 2 show completely different off-resonance behavior, even though the same trajectory, flipped in z-direction was used. It can be noted, that the images are distorted in the opposite direction. Assuming an off-resonance of 100/s and constant sampling over 75ms, the signal gets shifted in the z-direction by 3.6mm. This illustrates the shifts of the images and activation maps.

In the area of the sinuses signal dropout can be observed, especially in the image acquired with a negative z-gradient during read out (Figure 2, right). This can be explained by the z-gradient of the off-resonance (Figure 3). If the gradient of the off-resonance field points in the same direction as the encoding gradient, the image is distorted into the sinus and the encoding is unambiguous. When the encoding direction is turned around, the magnetic field has a local minimum. Therefore the encoding is ambiguous, making a meaningful reconstruction impossible in that part. Also the signal is distorted into the object, destroying the reconstruction even in regions, where the off-resonance is moderate.

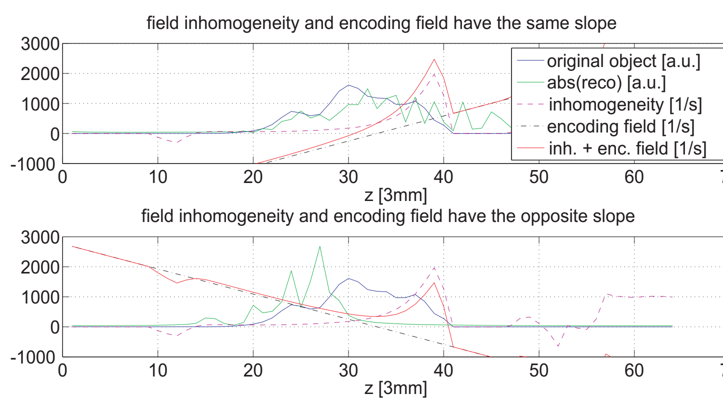

Figure 3: 1D-simulation of the off-resonance behavior of the stack of spirals trajectory. Depending of the direction of the encoding gradient relative to the gradient of the off-resonance, the encoding in ambiguous in parts.

Discussion: A SoS trajectory allows sampling of a full brain within 100ms. In difference to the shell trajectory [4], the SoS leads to distortions, rather than blurring and signal dropout. The loss of information can be minimized by choosing the right encoding direction. Avoiding signal dropout, off-resonance correction is possible [8]. Moreover, contrary to the shell trajectory [4], the SoS trajectory allows to reduce the FOV in z-direction, if partial brain images with improved spatial or temporal resolution are desired.

References: [1] Lin, FH., MRM 56:787–802 (2006); [2] Hennig J., Neuroimage 34(1):212-219 (2007); [3] Zahneisen, B., MRM 65:1260–1268 (2011); [4] Zahneisen, B., MRM (in press); [5] Irarrazabal, P., MRM 33:656-662 (1995) [6] Grotz, T., ISMRM 4381(2011); [7] Rudin L.,Physica D 60:259–268 (1992); [8] Zaitsev, M., MRM 52:1156–1166 (2004);