Ultra Fast Volumetric Functional Imaging using Single Shot Concentric Shells Trajectories

B. Zahneisen[1], T. Grotz[1], M. Zaitsev[1], and J. Hennig[1]
[1]University Hospital Freiburg, Freiburg, Germany

MR-encephalography (MREG) [1] has been shown to allow extremely fast and highly sensitive monitoring of functional activation. It is based on the use of small sensitive volumes in multi-coil arrays as an important source of spatial localization, highly undersampled 3D-trajectories and regularized reconstruction. Recently, it has been shown that the use of a 3D rosette trajectory provides whole brain coverage with an acquisition time of 23ms and a spatial resolution of 5-6mm^3 [2]. However, the rosette trajectory has a very non-uniform k-space sampling density and suffers from off-resonance artifacts. Here, we propose the use of a single shot, variable density, concentric shells trajectory for ultra-fast functional imaging. The uniform sampling density makes better use of the coil sensitivities. The insensitivity to off-resonances allows longer readout times and therefore provides better spatial resolution.

Materials and methods: All experiments were performed on a 3T scanner (Trio, Siemens) using a 32 channel head coil array for signal reception. For each session a reference volume was acquired with a 2D multi-slice GRE sequence (TR/TE=500/4.92). Coil sensitivities and an anatomical volume were derived from this dataset. Visual stimulation was performed by presenting a flickering checkerboard with alternating rest and stimulation periods (3x) each 10s long. During the presentation of the visual stimulation the subject performed a bilateral finger tapping task. For the retinotopic mapping experiment, a rotating wedge of the checkerboard was presented with 30s duration for a full rotation (3x). For functional imaging the following parameters were used: *FOV = 256mm³, N=64³, TR = 100ms.*

Trajectory: An analytical description for a spiral that travels on the surface of a spherical shell with radius k_R is given by $K(t)=(k_x,k_y,k_z)=(k_R \sin\Theta \cos(a\Theta), k_R \sin\Theta \sin(a\Theta), k_R \cos\Theta)$ with a parametric function $\theta=\theta(t)$ that ranges from 0 to π. The number of rotations on the shell is determined by the parameter *a*. For given *FOV* and resolution *N* ($\Delta k_{nyquist} = 1/FOV$), complete k-space coverage is achieved by using multiple shell elements. $M=N / (2R_{radial})$ shells with radius increment $\Delta k_{radial}=R_{radial}\ \Delta k_{nyquist}$ are needed for R_{radial}-fold acceleration in radial direction. The shell radius dependant parameter $a(k_R)$ for R_{polar}-fold undersampling in polar direction is given by $a = \pi/(\arcsin(R_{polar}\ \Delta k_{nyquist}\ /2k_R))$. Undersampling is therefore described by the two parameters R_{radial} and R_{polar}, which can be a function of k-space position. For ultra-fast fMRI, we propose the use of a variable density shells trajectory with an undersampling factor of R_1=2 at the center of k-space and linearly increasing to R_2=5 at the periphery of k-space, both for radial and polar direction. For single shot acquisition, consecutive shell elements are smoothly connected. An echo time is of 15ms is achieved by reordering the individual shell elements. Time optimal design of a single shell element is performed by ensuring that the gradient waveform always uses the maximum available slew rate S_{max}. An optimal $\theta=\theta(t)$ is found by expressing the slew rate as a second order differential equation $f(\ddot{\theta},\dot{\theta},\theta,\beta)=0$ in θ as proposed in [3] for spiral trajectories. A numerical solution of the differential equation provides the minimum time trajectory.

Image reconstruction: Offline image reconstruction was performed using MatLab (MatLab Inc.). It is based on solving the inverse problem given by $Ax = b$ where x is the unknown image, b is the measured data and A describes the forward operation of the measurement including coil sensitivity weights and measured trajectory. The solution is found by minimizing the function $f(x)=||Ax-b||^2 + \lambda||x||^2$ with respect to x, where λ is the regularization parameter [5].

Results: In Fig.1a, 3 elements of the shells trajectory are shown. Fig.1b displays the slew rate components of a single shell element. The numerical solution for $\theta(t)$ yields a trajectory that makes optimal use of the maximum slew rate (dashed line). In Fig.2 every 2nd transverse slice from a reconstructed volume is shown. The acquisition time was T_{ADC}=66ms.In Fig.3 dynamic T-maps show the activation as it passes through the subregions of the visual cortex that represent the stimulated visual fields. Fig.4 plots the BOLD response for voxels that are activated as the stimulation moves through the visual field (only 70s shown). The dotted line represents the maximum of the BOLD response that is shifted with the position.

Discussion: We present a method for ultra-fast volumetric functional imaging using single shot variable density concentric shells trajectories. The proposed acquisition scheme offers a homogenous coverage of 3D k-space and is less sensitive to off-resonance effects than a 3D-rosette trajectory. The method yields very good spatial localization and temporal resolution of BOLD-activation. The high sampling rate allows the real time observation of dynamic changes of the BOLD-response (dynamic retinotopic mapping)

[1] Hennig J, Zhong K, Speck O. Neuroimage 34(1):212-219(2007).
[2] Zahneisen, B, Grotz T, Hennig J. MRM 2010 (in press)
[3] Shu Y, Riederer SJ, Bernstein MA. MRM 56(3):553—562 (2006).
[4] King KF, Foo TK, Crawford CR. MRM 34(2):156—160 (1995)
[5] Grotz T, Zahneisen B, Hennig J., MRM 62:394-405 (2009)
This work is part of the INUMAC project supported by the German Federal Ministry of Research, grant #13N9208

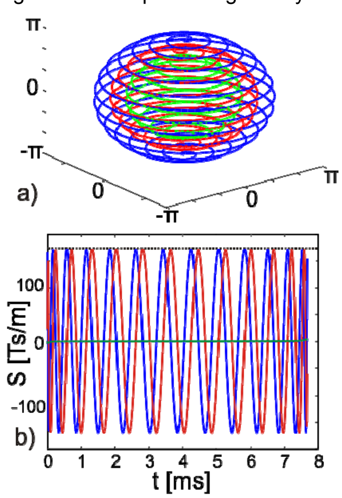

Fig.1 a) single shot concentric shells trajectory. b) optimal usage of slew rate by the proposed design method.

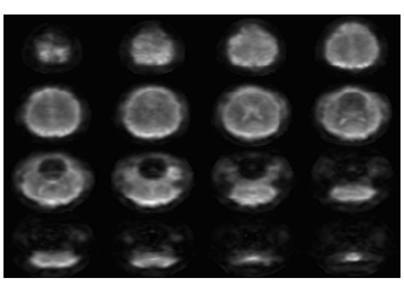
Fig.2) transverse slices from acquired volume T_{ADC} = 66ms.

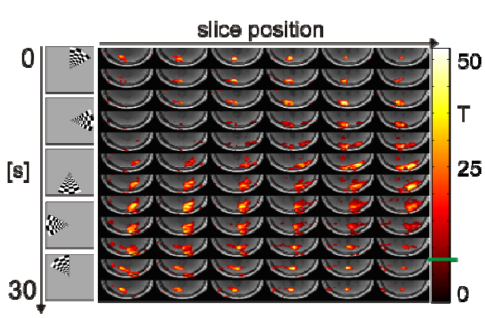

Fig.3) Dynamic retinotopic mapping by stimulation of visual fields with rotating checkerboard wedge

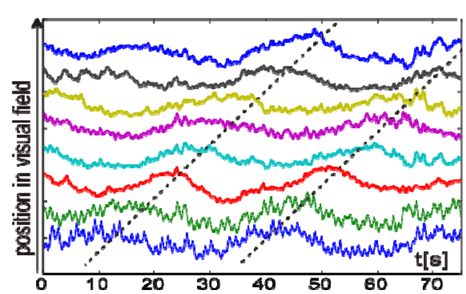

Fig.4) Single voxel BOLD responses from different positions in the visual cortex