Spatiotmeporal Fourier analysis of resting state fluctuations in BOLD fMRI of the rat

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Target Audience: Functional MRI (fMRI) and signal/image processing communities.

Background and purpose: Low frequency fluctuations (LFFs) in resting state fMRI signal have been used to map functional connectivity (FC) of the brain [1]. Presence of automatically detectable spatiotemporal propagation patterns has been reported previously in humans as well as rats [2, 3]. In this work, we demonstrate the utility of spatiotemporal Fourier transform (StFT) in studying the propagation characteristics of LFFs.

Methods: stFT of a 3D (2D+time) function *I(x, y, t)* is defined as $\Im(u,v,f) = \iiint I(x,y,t)e^{-2\pi i(ux+vy+ft)}dxdydt$, where *u* and *v* are spatial frequencies (mm^{-1} in our case) and *f* is temporal frequency (Hz). A useful interpretation of stFT is that it decomposes the spatiotemporal data into propagating waves of different temporal frequencies, speeds, directions and phases. For example, $\Im(u,v,f) = \delta(u-u_0, v-v_0, f-f_0) + \delta(u+u_0, v+v_0, f+f_0)$ corresponds to a sinusoidal propagating wave in the direction of the vector $-u_0\hat{x} - v_0\hat{y}$ with temporal frequency f_0 and speed $f_0/\sqrt{(u_0{}^2+v_0{}^2)}$. In this study, we utilize discrete version of stFT to study the LFFs in rat brain. *Animal Imaging* was performed on 9.4T Bruker scanner. The rats were sedated using medetomidine. For each rat, a series of gradient echo EPI images was acquired of 4-5 coronal slices with following parameters: TR = 500 ms, TE = 20 ms, matrix size = 64x64, in-plane resolution = 300-400 microns, 1200 repetitions. Only one slice (covering somatosensory cortex and caudate-putamen (CP)) was used for the analysis. *Preprocessing* included spatial blurring, temporal filtering (0.08-0.2 Hz), and normalizing of each time series to unit variance. Preprocessed data is referred to as $I_1(x,y,t)$. *Spatiotemporal pattern detection* was performed using the iterative algorithm proposed in [3]. ROI based on the cortex was used to obtain the pattern consisting of lateral-to-medial propagating waves reported in [2, 3] (referred to as $I_2(x,y,t)$). *Discrete stFT* was performed on $I_1(x,y,t)$ and $I_2(x,y,t)$ to obtain $\Im_1(u,v,f)$ and $\Im_2(u,v,f)$ respectively. Based on $\Im_2(u,v,f)$, spatiotemporal filtering was performed on the $I_1(x,y,t)$ in frequency domain (with zero-padding to minimize artifacts due to circular convolution) to enhance the components present in $I_2(x,y,t)$ and a new template $I_3(x,y,t)$ was obtained using the spatiotemporally filtered data.

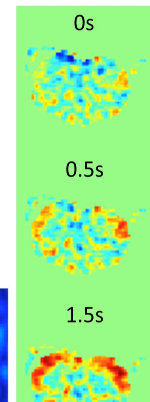

Fig 1

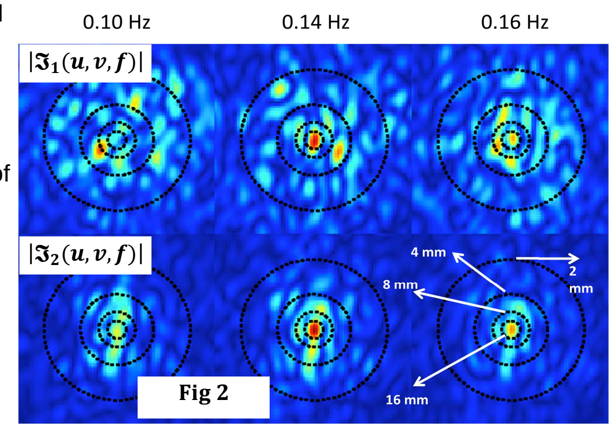

Fig 2

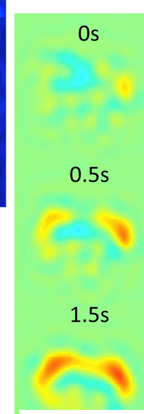

Fig 3

Results and Discussion: Fig 1 shows a few frames of $I_2(x,y,t)$. Lateral-to-medial propagation in the sensorimotor cortex can be seen, consistent with [2, 3]. Fig 2 shows $|\Im_1(u,v,f)|$ and $|\Im_2(u,v,f)|$ for 3 values of *f*. The spectra were individually normalized between 0 and 1 for display purposes. The points on the each dotted circle correspond to the same spatial wavelength $1/\sqrt{(u^2+v^2)}$ (as indicated on the figure) and speed $f/\sqrt{(u^2+v^2)}$. Components with a broad range of velocities are present in $I_1(x,y,t)$ for the temporal frequencies indicated on Fig 2, whereas the spectrum of $I_2(x,y,t)$ is dominated by components with higher velocities (and larger spatial wavelengths) for the same temporal frequencies. This observation suggests that the lateral-to-medial propagation pattern consists of spatially fast propagating components of LFFs. The blur in vertical direction (as seen in $|\Im_2(u,v,f)|$) can be attributed to restricted propagation in vertical direction. Based upon these results, the aforementioned frequency-domain spatiotemporal filter was designed to be a "high-velocity" filter (keeping velocities of 0.5mm/s and above). As expected, the spatiotemporal pattern isolated using the iterative algorithm [3] after "high-velocity" filtering results in more noise-free propagating wave in lateral-to-medial direction (Fig 3).

Conclusions: stFT decomposes the data into propagating waves with different dynamic properties, and hence can be a natural tool for studying and identifying different "building blocks" of LFFs with different dynamic characteristics. Such techniques can also offer a useful tool to analyze and process dynamic imaging data. Our results suggest presence of slow-moving contributions towards the data that are not present in the lateral-to-medial cortical waves (Fig 2), and future work will focus on exploring those contributions.

References [1] Biswal B et al. Magn Res Med 1995; 34:537-541 [2] Majeed, W et al. JMRI 2009; 30:384-393 [3] Majeed, W et al. NeuroImage 2011; 54(2):1140-1150