Isotropic, high-resolution FMRI at 7T using 3D stack-of-segmented EPI

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INTRODUCTION. High resolution FMRI is of interest for the study of fine cortical architecture [1–4], but difficult to achieve due to the decrease in SNR that accompanies a reduction in voxel volume. One approach is to acquire standard 2D multi-slice FMRI data with hardware that increases the available SNR (e.g., localized receive coils and/or higher field strength). While these approaches can achieve sufficient SNR to support small voxel volumes, in practice the achievable voxels are highly anisotropic because slice-selective RF pulses cannot reliably define slices less than 1–2 mm thick. The resultant data is able to resolve fine architecture in-plane, but typically has a through-plane dimension that is 3–10 times greater than the in-plane dimension. Given that the cortex does not in general follow a planar orientation, but rather is a highly convoluted 3D structure, the ability to acquire high-resolution, isotropic data is of crucial importance for the study of cortical architecture, such as retinotopic maps of visual cortex. An alternative approach is to acquire 3D k-space data, which can achieve similar voxel dimensions in all directions. However, to our knowledge, high-resolution, 3D FMRI has not previously been demonstrated at high field. In this work, we demonstrate isotropic, high-resolution FMRI in the human brain at 7T using a 3D extension of segmented EPI.

METHODS. We acquire segmented EPI with additional phase encoding along the z direction, resulting in a series of segmented EPI readouts stacked along k_z (Fig. 1) [4]. This stack-of-segmented EPI readout has a high duty cycle and enables fast volume acquisitions while retaining flexibility in the duration of each segment in order to allow tradeoffs in distortion, signal dropout, T_2 blurring and SAR. Phase correction measurements for each 3D EPI volume are acquired in a separate T_R, consisting of three lines centered at the echo time (roughly $T_R/2$). For typical T_1 at 7T (1750–2000 ms) and T_R used in these experiments (34–36 ms), the Ernst angle is sufficiently small (11°) to remain within SAR limits.

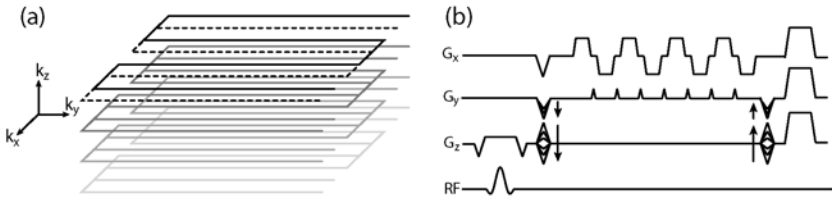

FIGURE 1. (a) 3D trajectory acquiring segmented EPI in a series of planes (x,y) stacked along the 3rd dimension (z). (b) 3D pulse sequence with EPI blips along y and phase encoding along z (8 lines are shown per segment).

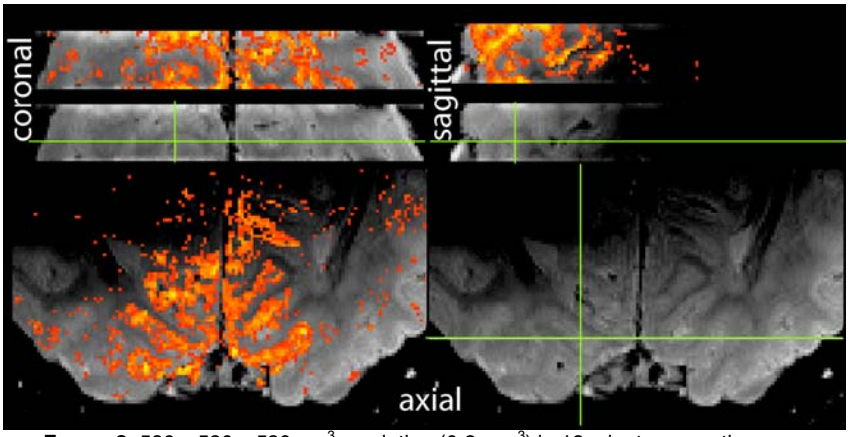

FIGURE 2. 580 x 580 x 580 μm^3 resolution (0.2 mm^3) in 18 minutes scan time.

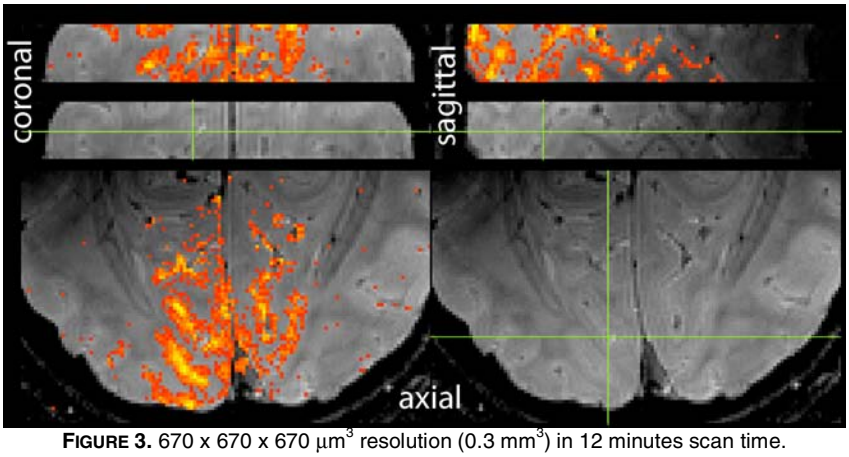

FIGURE 3. 670 x 670 x 670 μm^3 resolution (0.3 mm^3) in 12 minutes scan time.

EXPERIMENTS. Healthy human subjects were studied on a Siemens 7T scanner equipped with an insert gradient coil (maximum 100 mT/m amplitude and slew rate 800 mT/m/s) and an 8-channel receive array fitted into a volume transmit coil (only the three posterior elements were used). To date, five subjects have been scanned with voxel volumes ranging from 0.19-0.42 mm^3 (isotropic cubic voxel dimensions 580-750 μm). Slices were oriented along the calcarine fissure. Typically, 10 segments per plane and 20 slices (200 total segments) were acquired, with a complete volume was every ≈7 s. Runs were 3–4 minutes long with 30s on / 30 s off visual stimulation blocks (yellow-blue flashing annular checkerboard patterns); repeated measures of three to six runs were acquired. No spatial smoothing or cluster-based thresholding was performed.

RESULTS AND DISCUSSION. Example data are shown in Figs. 2-3, with activation maps displayed on the mean GRE images. Images are of high quality, with little visible artifact other than a shear due to B_0 drift and a single visible fat ghost at FOV/20 (which was placed outside the brain with A>>P phase encoding). These data demonstrate the complicated structure of visual cortex, which follows a convoluted path in three-dimensional space. Although the useful properties of 3D trajectories have been recognized previously, these methods have received limited attention in FMRI, due in part to limitations in achievable coverage. When applied to 3D trajectories, parallel imaging methods have potential to significantly increase coverage with only modest loss of SNR, which may be highly beneficial for 3D FMRI studies.

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[1] Menon, MRM (1999). [2] Hoogenraad, MRI (2000). [3] Kim, Nat Neurosci (2000). [4] Duong, MRM, (2002). [5] Miller, MRM (2006).