Hadamard-Encoded fMRI for Reduced Susceptibility Dropout

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Introduction: BOLD fMRI suffers from signal dropout in frontal-orbital and lateral parietal/temporal regions where the difference in susceptibility between air cavities and tissue induces Bo field gradients that cause intravoxel dephasing. By decreasing the slice thickness, dephasing is reduced and signal is regained, but at the expense of signal to noise ratio (SNR) in magnetically uniform regions of the brain (1). This SNR penalty can be partially mitigated by incoherent combination of adjacent thinner slices, but the penalty is still severe because fewer time frames can be acquired to obtain the same brain coverage. For example, acquiring 2 mm slices and combining 2 slices to create an equivalent 4 mm acquisition will have a net SNR half that of a 4 mm slice acquisition for the same total scan time. Thus thin slices are not practical. Here we introduce a novel solution: the use of Hadamard-encoding to simultaneously excite pairs of subslices that are subsequently combined incoherently using UNFOLD (2) to gain signal in dropout regions at no loss of SNR efficiency in uniform regions.

Methods: Alternately applying sine- and cosine-modulated Hadamard pulses (3) in a dynamic acquisition, two sub-slices of half the desired slice thickness are excited in-phase and out-of-phase (Fig. 1). Assuming there is a phase shift of ϕ between subslices because of the susceptibility-induced gradients, the resulting complex-valued time series contains magnitude components $y(t) = \left[\rho_1^2(t) + \rho_2^2(t) \mp 2\rho_1(t)\rho_2(t)\sin(\phi(t))\right]^{1/2}$, where ρ_i are the magnitudes of the subslice signals, and the sign alternates with time frame *t* because of the alternating excitation. Squaring y(t) and taking its Fourier transform, one finds a component Y_1 with spectrum centered at DC corresponding to the term $\rho_1^2(t) + \rho_2^2(t)$ and a second component Y_2 centered at the Nyquist frequency corresponding to $2\rho_1(t)\rho_2(t)\sin(\phi(t))$ (Fig. 2). Applying an UNFOLD filter $H(\omega)$ to remove the Nyquist component, inverse transforming and taking the square root yields a reconstructed timeseries $\rho(t) = \left\{\Im^{-1}\left[\Im\left(y^2(t)\right)H(\omega)\right]\right\}^{1/2} = \left[\rho_1^2(t) + \rho_2^2(t)\right]^{1/2}$, i.e. the square root of the sum of squares of the two subslices. The influence of the intravoxel dephasing component ϕ is thereby removed (although dephasing within the thinner subslices remains). It can be shown that in the absence of dephasing, the SNR of ρ is the same as that of a conventional acquisition with slice width twice that of the subslices.

The Hadamard method was implemented in a spiral-in/out pulse sequence (4) using excitation pulses derived from a Hamming-weighted sinc pulse with 1.25 kHz bandwidth and ±4π duration (6.4 ms). 60 2 mm thick subslices were acquired for 128 time frames (TR/TE = 2s/30ms, 3.43mm in-plane resolution). Timeseries corresponding to 4 mm slices were obtained from the magnitude reconstructed images as above using a two-point boxcar filter ($H(\omega) = \cos(\omega/\omega_{Nyq})$). Functional data were obtained at 3T (GE Discovery 750) from two volunteers who provided informed consent in accord with the IRB. A breath hold task was employed to elicit activation in most of the brain (5). For comparison, acquisitions were also obtained with a conventional spiral-in/out sequence having 30 4 mm slices, the same temporal filtering and other parameters the same. Two runs were acquired using each method and results averaged across repetitions.

Results: Figure 3 shows SFNR and activation maps for one volunteer. Note the recovery of signal in susceptibility regions and increase in SFNR from reduction of phase noise in the incoherent addition of subslices. Using the ROIs shown to highlight the compromised regions (green boxes, Fig. 3), an increase of 10.0% in activation extent was obtained with the Hadamard method.

Conclusion: The new method shows promise in diminishing signal dropout without loss of SNR efficiency, but with small loss in temporal resolution. Future work will include extension to more than 2 subslices and use of the inter-slice phase information (that can be obtained from the Nyquist term Y_2) for adaptive compensation in the Hadamard pulse design.

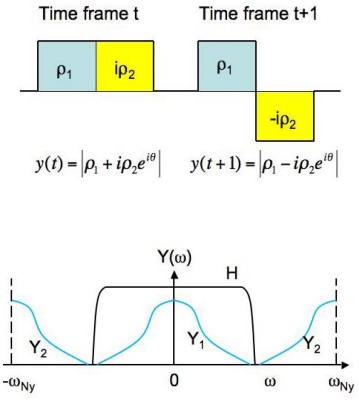

Fig. 1 (left, top). Two time frames, showing Hadamard excitation of subslices ρ_i with alternating phase of ρ_2.

Fig. 2 (left, bottom). Spectrum of squared time series. Desired component $Y_1(\omega)$ centered at DC is selected by UNFOLD filter H.

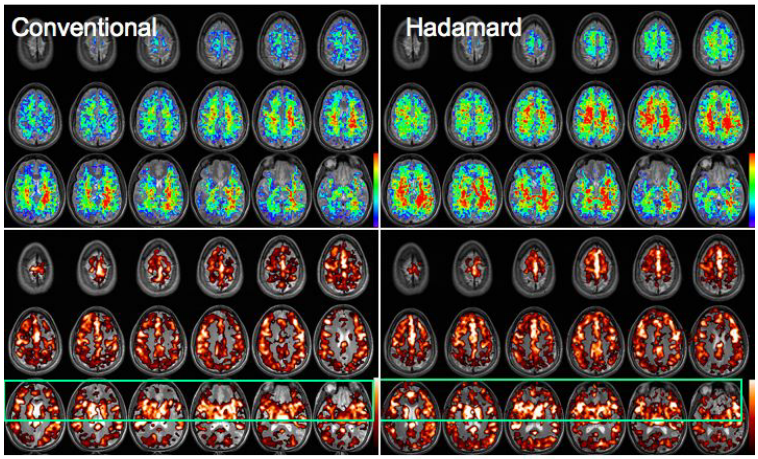

Fig. 3 (right). SFNR maps (top, 90-140) and activation maps (bottom, p<0.05) for one subject. Note increase in SFNR and activation with new method, especially in frontal regions, and slight gains in uniform regions.

References: 1. Lai S, et al. Magn. Reson. Med 39:68 (1998). 2. Madore B, et al. Magn. Reson. Med 42:813 (1999). 3. Souza SP, et al. J. Comp. Assist. Tomog. 12:1026 (1988). 4. Glover GH, et al. Magn. Reson. Med 46:515 (1998). 5. Thomason ME, et al. NeuroImage 25:824 (2005).

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