Increased temporal resolution in fMRI using Hadamard-encoding with phase correction and physiological noise removal

Alan Chu[1], Jon-Fredrik Nielsen[1], and Douglas C. Noll[1]

[1]*Biomedical Engineering, University of Michigan, Ann Arbor, Michigan, United States*

INTRODUCTION: Hadamard-encoded (H-encoded) fMRI [1] is a multi-slice acquisition method that uses an RF pulse to encode a slab of subslices [2]. Individual subslices can be extracted or decoded using a temporal filter during post-processing. Because H-encoding acquires multiple subslices with each excitation, it can excite the same object volume in a shorter amount of time compared to conventional single-slice fMRI, potentially resulting in an increased temporal resolution. However, H-encoded fMRI is more sensitive to signal variations induced by both physiological and non-physiological sources. Therefore, it is important to perform sufficient noise suppression in order for H-encoded fMRI to realize its advantages.

THEORY: To acquire 2 subslices per slab, H-encoded fMRI uses a frequency-modulated Hamming-weighted sinc function [1] $r(t) = [\exp(-i\pi f_0 t) + i(-1)^n \exp(i\pi f_0 t)]\text{sinc}(f_0 t)[0.54 + 0.46\cos(2\pi t/T)]$ for the RF pulse, where $|t| \leq T/2$, where T is the duration of the pulse, f_0 is the bandwidth of the sinc, and $n = 0, 1, \ldots, N-1$ is the time frame of the pulse for N frames. The nonalternating subslice whose excitation phase does not alternate with time is decoded using a low pass filter. The alternating subslice is decoded by modulating the timeseries by $i(-1)^{n-1}$, then using the same low pass filter.

Physiological noise has a greater impact on H-encoded fMRI than conventional fMRI. In H-decoding, each subslice needs data from at least 2 excitations, which can occur at different positions in a physiological motion cycle. In addition, physiological noise can affect the time series image phase, which is important for the H-decoding process, but typically ignored in conventional fMRI.

Unintended non-physiological time series phase variation is also problematic for H-encoded fMRI. The low pass filter relies on the phase difference from time frame to time frame introduced by the $i(-1)^n$ term in the RF pulse. It is critical for proper subslice decoding that the alternating subslice has excitation phase that is 180° away from its excitation phase in the previous time frame. Variations in this excitation phase say, from head motion, will cause signal from the alternating subslice to contaminate the nonalternating subslice after decoding. If the phase for odd n frames is set to the mean phase for odd n, and similarly for even n, the subslice separation will be more clean. Figure 1 illustrates the phase correction method. The voxel magnitudes are not altered in this process.

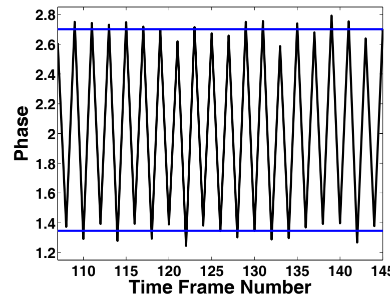

Fig. 1: Phase correction method. Odd and even-numbered phases are set to their mean. (Original phase time series in black, corrected values in blue.)

Increased temporal resolution can be obtained by using a low pass filter with cutoff greater than 0.25 times the fMRI sampling frequency. Note that H-encoded fMRI can cover the same volume of an object as in conventional fMRI, but in half the time if the width of each Hadamard pair is set to be twice the width of a conventional fMRI slice. In other words, if a conventional pulse sequence needs a TR_{conv} of 2 seconds to cover forty 3 mm slices, the same sequence with H-encoding can cover twenty 6 mm pairs with a TR_{Hada} of 1 second. If the cutoff for the decoding filter is greater than $0.25/TR_{Hada}$ Hz, then the temporal resolution for H-encoded fMRI will be greater than that for conventional fMRI. Having a decoding filter cutoff of greater than $0.25/TR_{Hada}$ Hz will not significantly degrade the quality of decoding since most of the frequency content of each subslice is located in a relatively narrow bandwidth around 0 Hz and around $0.5/TR_{Hada}$ Hz, as shown in Figure 2.

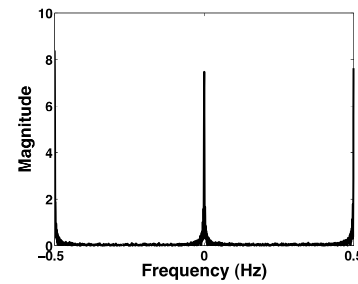

Fig. 2: Single voxel time series spectrum of H-encoded data, where TR_{Hada} = 1 s.

METHODS: Scans of 11 subjects were acquired using a visual stimulus block paradigm. Each subject was scanned once using H-encoding and once without, which served as the conventional comparison. For the H-encoded scans, twenty 6 mm slabs (pair of subslices) were acquired using $T = 8$ ms, $f_0 = 1$ kHz, $N = 490$ time frames, and a spiral-in sequence with a TR_{Hada} of 1 s. For the conventional scans, forty 3 mm slices were acquired using a Hamming-weighted sinc pulse with duration 8 ms, bandwidth 1 kHz, $N = 245$ time frames, and a spiral-in sequence with a TR_{conv} of 2 s.

Physiological noise was removed for the H-encoded and conventional scans by regressing out first and second order Fourier series terms from the magnitude and phase time series [3]. For the H-encoded scans, the regression was performed separately on the odd-numbered time frames and separately on the even-numbered frames. Next, phase correction was performed on the H-encoded data as described above before employing the temporal filter to decode the subslices. The temporal filter was an FIR filter with cutoff approximately $0.316/TR_{Hada}$ Hz.

Since the temporal resolution of the processed data from the H-encoded scans is greater than that of the conventional scans, a comparison of single-threshold activation would not be fair. Therefore, test-retest reliability [4] was used to determine the quality of the activation computation for Hadamard versus conventional. For each subject, 5 different processing schemes were compared, as shown in the Figure 3 legend. ROC curves were generated for each processing scheme using different t-score thresholds for activation. The approximate area under each ROC curve was computed as a measure of activation quality. Figure 3 shows the 5 ROC curves for one particular subject.

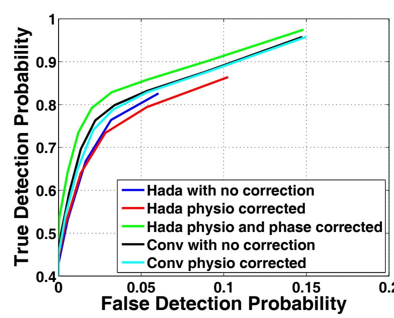

Fig. 3: ROC curves for one subject. Here, H-encoding with physio and phase correction had the highest activation quality because the area under its ROC curve was the greatest.

RESULTS: Table 1 shows the mean across subjects of the area under the ROC curve for each processing scheme. The mean for Hadamard with physio and phase correction is higher than either conventional processing scheme, but pairwise *t*-tests were not significant due to intersubject and intertrial variability. However, Hadamard with physio and phase correction was significantly better than either Hadamard with no correction (p-value of 0.0021) or Hadamard with physio correction only (p-value of 0.00024).

	Hada	Hada Physio	Hada Physio Phase	Conv	Conv Physio
Mean	1.9663	2.0795	2.3717	2.1229	2.0992

Table 1: Across-subject mean of area under ROC curve. Units are arbitrary and comparative.

CONCLUSION: H-encoding provides a simple and flexible way to increase the temporal resolution of fMRI without a decrease in activation quality. However, due to the nature of H-encoding, phase correction and physiological noise removal are needed for proper subslice decoding.

REFERENCES AND ACKNOWLEDGEMENTS: [1] Glover et al. 2010. Proc Intl Soc Mag Reson Med. Page 272. [2] Souza et al. 1988. J Comput Assist Tomo. 12(6):1026. [3] Glover et al. 2000. Magn Reson Med. 44:162. [4] Noll et al. 1997. Magn Reson Med. 38:508.

This work is supported by the Howard Hughes Medical Institute.