# Increased SNR and activation in Hadamard-encoded fMRI through physiological noise removal and phase correction

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**Introduction:** Hadamard-encoded (H-encoded) fMRI [1] is a method that acquires a slab of multiple subslices with each RF excitation [2]. The subslices can then be extracted using temporal filtering, analogous to UNFOLD [3]. By setting the subslice width equal to that of a conventional fMRI scan, SNR is increased because of the larger slab thickness. However, since H-encoding uses complex data for subslice extraction, noise from physiological sources such as respiration and cardiac pulsatility can have a large effect on image integrity and functional activation. In this abstract, we introduce both physiological noise removal and phase correction in H-encoded fMRI, and compare the resulting functional activation with that of a conventional fMRI scan.

**Theory:** In this work, each slab is composed of 2 subslices for H-encoded fMRI. The RF pulses consist of a frequency-modulated Hamming-weighted sinc function [1] $\mathrm{r}(t) = [\exp(-i\pi f_0 t) + i(-1)^n \exp(i\pi f_0 t)]\,\mathrm{sinc}(f_0 t)[0.54 + 0.46\cos(2\pi t/T)]$, where $|t| \le T/2$, where $T$ is the duration of the pulse, $f_0$ is the bandwidth of the sinc, and $n = 0, 1, ..., N-1$ is the time frame of the pulse for $N$ frames. A low-pass filter is used to extract the subslice whose excitation phase does not alternate in time. To extract the other subslice, the original timeseries data is first multiplied by $i(-1)^{n-1}$, then low-pass filtered.

Physiological noise causes variations in not only the magnitude of the data, but also the phase. Since the temporal filter operates on complex data for subslice extraction, signal variations from physiological motion can potentially have a greater effect on H-encoded fMRI when compared to a conventional scan, where only the magnitude data is important for voxel activation. Therefore, physiological noise removal can potentially greatly increase the statistical correlation of activated voxel timeseries to a task in H-encoded fMRI.

A phase correction scheme is also used to enhance activation. The only difference between the excitation for each subslice is the $i(-1)^n$ term in the RF pulse, which offsets the phase for that subslice by 90° or –90°, depending on the time frame. The temporal filtering used for subslice extraction is entirely dependent on this phase change from frame to frame. If the phase change varies, the temporal filter will not separate the subslices as cleanly. Therefore, for each complex voxel timeseries, setting the phase for odd $n$ frames equal to the mean phase for odd $n$, and doing similarly for even $n$ results in better separation.

**Methods:** Two scans were acquired: one using H-encoding and one without, which served as the conventional comparison. For both scans, the same visual stimulus and right finger tapping task was performed in a blocked paradigm. The H-encoded scan was acquired with twenty-one 6 mm-thick slabs of two 3 mm subslices using the Hamming-weighted alternating RF pulses described above, with $T$ = 6.4 ms, $f_0$ = 1.25 kHz, and $N$ = 300 time frames. A spiral-in sequence was used with a TR of 1 s, TE of 30 ms, and flip angle of 62°. Slices were acquired in interleaved order to reduce signal cross-talk.

The conventional scan was acquired with forty-two 3 mm thick slices using a Hamming-weighted sinc pulse with duration 6.4 ms, bandwidth 1.25 kHz, and 150 time frames. The same spiral sequence was used with a TR of 2 s, TE of 30 ms, and flip angle of 77°. Slices were also acquired in interleaved order. For the conventional scan, a TR twice that of the Hadamard scan was necessary to minimize the differences in effective temporal resolution.

Physiological noise was recorded using a pulse oximeter for cardiac and a pressure belt for respiratory motion. Noise removal was performed for both scans by regressing out 1st, 2nd, and 3rd order trends, and employing RETROICOR on the magnitude and phase data [4]. However, for the Hadamard scans, the regression was performed on the odd and even-numbered time frames separately due to the nature of the encoding. Finally, the phase correction method described above was applied to the Hadamard scan before low-pass filtering.

| | Correction: | | |
|---|---|---|---|
| | None | Physio | Physio and Phase |
| Hadamard | 0.1413 | 0.1814 | 0.2437 |
| Conventional | 0.1803 | 0.1928 | — |

**Table 1:** Ratio of activated voxels to brain voxels in the visual cortex areas encircled in Fig. 1. Correlation coefficient threshold of 0.35 (*p*-val < 6.3e–5) used to determine activation.

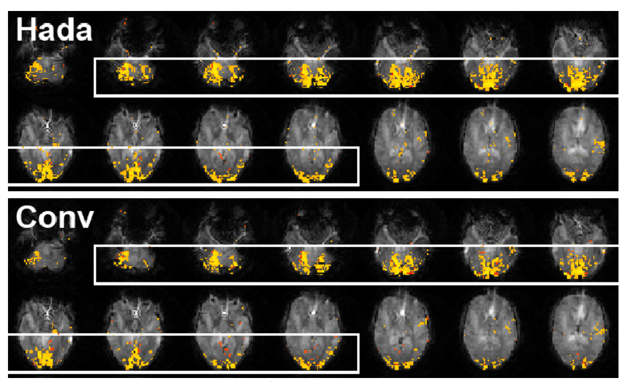


**Fig. 1:** Activation overlays of 1 subject using H-encoded (top) and conventional (bottom) scans. Visual cortex areas used for activation comparison in Table 1 are encircled in white.

**Results:** From Table 1, note the larger effect of physiological noise removal for H-encoding than for the conventional scan. Also note the large increase in activation with phase correction in H-encoding. In Figure 2, the correlation coefficient for this voxel improves from 0.6475, to 0.7177, to 0.8510 with each additional correction in H-encoding.

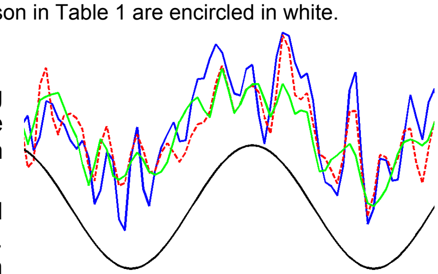

**Fig. 2:** Timeseries of a voxel without any correction (blue), with only physio correction (dotted red), and with both physio and phase correction (green). Paradigm (black).

**Conclusion:** H-encoded fMRI, along with the appropriate physiological noise removal and phase correction, can potentially increase the SNR and result in better voxel activation. Further investigation is warranted to examine the effects of filtering and phase correction on temporal resolution and false activation, along with the statistical significance of the increase in activation.

**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] Madore et al. 1999. Magn Reson Med. 42:813. [4] Glover et al. 2000. Magn Reson Med. 44:162. This work is supported by the Howard Hughes Medical Institute.