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Achieving high temporal resolution using a sliding-window approach for SPARKLING fMRI data: A simulation study

Amor Zaineb¹, Comby Pierre-Antoine^{1,2}, Ciuciu Philippe^{1,2}, and Vignaud Alexandre¹

¹Université Paris-Saclay, CEA, NeuroSpin, CNRS, Gif-sur-Yvette, France

²Université Paris-Saclay, Inria, MIND, Palaiseau, France

1 Synopsis

In light of the mounting interest in temporal resolution in BOLD fMRI, we explore the sliding-window approach, specifically using the SPARKLING encoding scheme. A simulation study is conducted for 2D BOLD fMRI and demonstrates the possibility through the sliding window approach to detect oscillations beyond 0.2Hz in the BOLD response and separate the physiological noise from the neural activity by improving the temporal resolution.

2 Summary of findings

In this work, we conduct 2D BOLD fMRI simulations using the SPARKLING encoding scheme to explore the advantages of a sliding-window reconstruction for improved temporal resolution. Our findings show that it is possible to detect oscillations beyond 0.2Hz and disentangle physiology from neural activity using this approach.

3 Introduction

As an indirect measure of neural activity, blood oxygenation level-dependent (BOLD) effect [1] has slower dynamics than the neural activity itself, partly due to the data acquisition process and partly due to the sluggishness of the hemodynamic response function (HRF) [2]. However, while the slowness of BOLD with regard to neural events is widely acknowledged, its inherent temporal resolution remains ambiguous. Despite some precursor interest [3, 4], the temporal dimension received less attention than the spatial dimension, as fMRI was primarily used as a brain mapping tool. Nevertheless, this has changed in recent years primarily because of a greater interest in the high-frequency components of BOLD [5–7] but also because high temporal resolution is essential to get rid of physiological artifacts related to breathing or heart rate [8, 9]. Most current attempts

28 achieve high temporal resolution at the expense of either diminished brain coverage [10, 11] or a
29 loss in spatial resolution [12, 13]. The assumption of repeatability has also been used to enhance
30 temporal resolution [14] as well as sharing data between different frames [15–17]. In this context,
31 we re-investigate the sliding-window approach introduced in [15] and demonstrate its ability detect
32 oscillations beyond 0.2Hz and to disentangle physiology from neural activity in simulations of 2D
33 BOLD fMRI using non-Cartesian In-Out SPARKLING [18, 19] sampling pattern (characterized by
34 the fact that each shot crosses the center of k-space at the echo time) in a scan-and-repeat mode.

35 4 Materials and methods

36 To study the potential benefit of the sliding-window approach applied to 2D SPARKLING BOLD
37 fMRI, simulated data was synthesized according to the pipeline presented in Fig. 1:

38 **(A) Highly temporally-resolved simulated neural activity:** Two types of neural events are
39 convolved with the Glover HRF to produce the ground truth or reference for slow and fast
40 BOLD responses at a temporal resolution of 0.1s.

41 **(B) Highly temporally-resolved ground truth of 2D fMRI frames:** The BOLD responses
42 in **(A)** are used to modulate the magnitude of the voxels of a chosen region of interest (ROI)
43 in a sequence of a 2D (1mm^2 and $(192\times 192)\text{mm}^2$ FOV) numerical brain phantom.

44 **(C) Highly temporally-resolved physiological and thermal noises:** Gaussian noise and
45 breathing fluctuations are emulated over all voxels. A given signal-to-noise ratio (SNR) is
46 chosen, and the maximum intensity change due to breathing fluctuations is defined as 0.2% of
47 the baseline magnitude. The SNR here equals the temporal SNR.

48 **(D) Retrospective k-space sampling:** The k-space data is synthesized by sampling each 2D
49 frame using 2 consecutive shots (from a complete sampling pattern of 48 shots), meaning at a
50 pace of 0.1s since each shot corresponds to $TR_{shot} = 50\text{ms}$. Therefore, every 24-period spaced
51 frames are sampled using the same trajectories.

52 **(E) Sequential fMRI image reconstruction at the native TR ($TR_{native}=2.4\text{s}$):** The k-
53 space data generated in **(D)** is gathered to form 48-shot blocks. Such a large number of
54 shots (and therefore TR_{native}) is not necessary for a single MRI slice and reflects more a
55 3D acquisition setup. Here, we chose, however, to proceed in 2D for the sake of simplicity,
56 computational efficiency, and demonstration. The reconstruction is performed using a simple
57 zero-filled adjoint.

58 **(F) Sliding-window fMRI image reconstruction at the effective TR ($TR_{eff}=0.6\text{s}$):** A
59 sliding-window approach of width and stride of 48 and 12 shots, respectively, is used to recon-
60 struct consecutive frames from overlapping k-space data.

Figure 1: fMRI Simulation pipeline: Highly temporally-resolved (A) simulated neural activity, (B) reference of 2D fMRI frames (The maximum intensity change due to (A) is defined as 5% of the baseline magnitude) and (C) physiological and thermal noises. (D) Retrospective k-space sampling: SPARKLING sampling pattern is used in a scan-and-repeat mode. (E) Sequential and (F) Sliding-window fMRI image reconstruction at TR_{native} and TR_{eff} respectively.

5 Results

Through two scenarios, the first characterized by a fast BOLD response and the second by a slow one, Fig. 2 showcases the ability of the sliding-window approach to reveal some high-frequency neural activity/dynamics as it enables the tracking of rapid fluctuations.

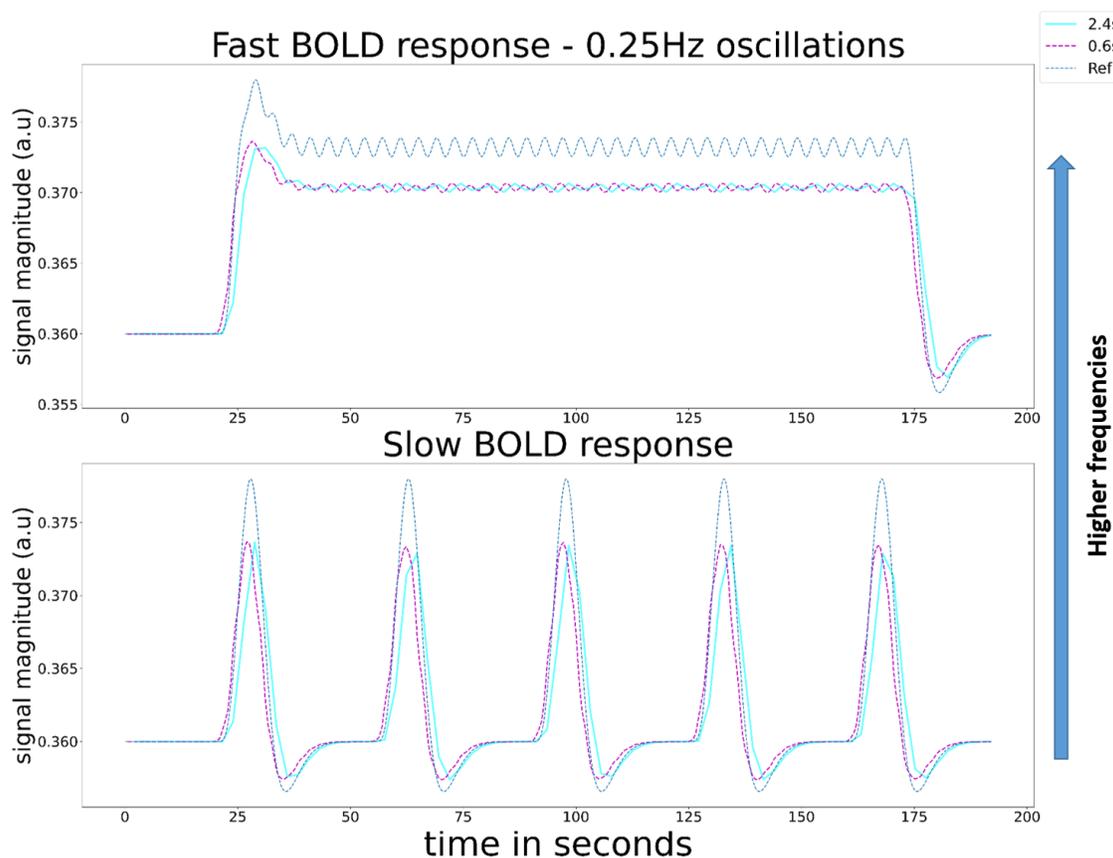


Figure 2: Time courses in a activated single voxel, of the reference BOLD response vs. that estimated using a sequential (resp., sliding-window) reconstruction at a $TR_{native} = 2.4s$ (resp., $TR_{eff} = 0.6s$). Two scenarios are illustrated, namely slow and fast (0.25Hz-oscillating HRF). As the temporal dynamics become faster, the sliding-window approach becomes more relevant as it allows for a better temporal segmentation of the signal.

Fig. 3 demonstrates that it is possible to track BOLD fluctuations at 0.25Hz for up to SNR=100.

Fig. 4 shows that it's possible to effectively resolve and separate physiological noise from neural activity using the sliding-window technique.

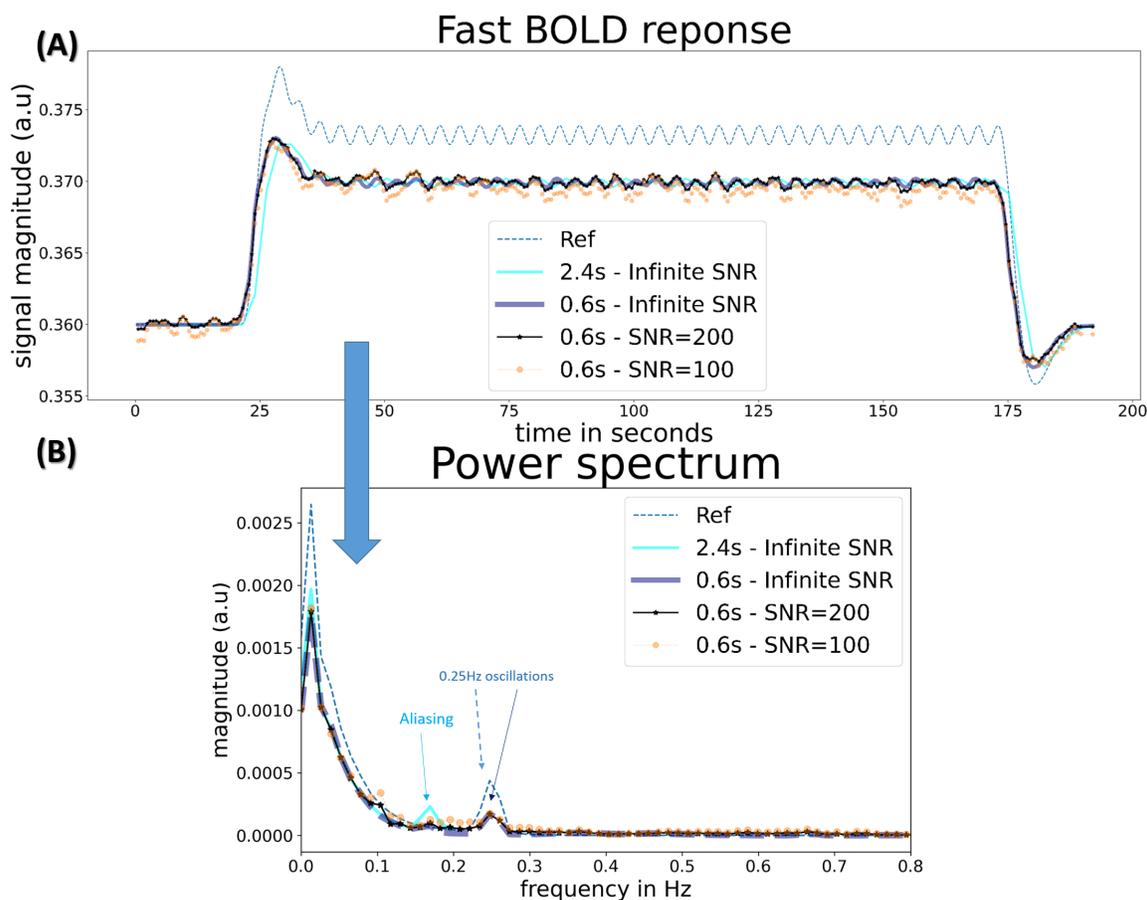


Figure 3: (A) Time courses in a single activated voxel, and (B) corresponding power spectra of a reference fast BOLD response vs. those estimated simulated data (assuming an infinite SNR, SNR=200 and SNR=100) using a sequential (resp., sliding-window) reconstruction at a $TR_{native} = 2.4s$ (resp., $TR_{eff} = 0.6s$). By contrasting the exceedingly optimistic SNR of 200 with the more realistic SNR of 100, we note that a sufficiently high SNR is required to be able to detect these oscillations.

68 6 Discussion

69 As neural events become faster, the convolution with the conventional HRF model [2] is expected to
 70 produce highly attenuated oscillations in the BOLD response that can be easily drowned in thermal
 71 noise. This is why we chose to stick to 0.25Hz BOLD oscillations for the sake of demonstration.
 72 $TR_{eff}=0.6s$ is sufficiently short to detect such oscillations. However, shorter TR_{eff} are achievable.
 73 Furthermore, in [5], the authors demonstrate that fast BOLD oscillations detected in vivo have
 74 higher amplitudes than those expected theoretically. The ability of the sliding-window approach to
 75 detect high-frequency oscillations in BOLD responses in vivo ought to be further investigated.

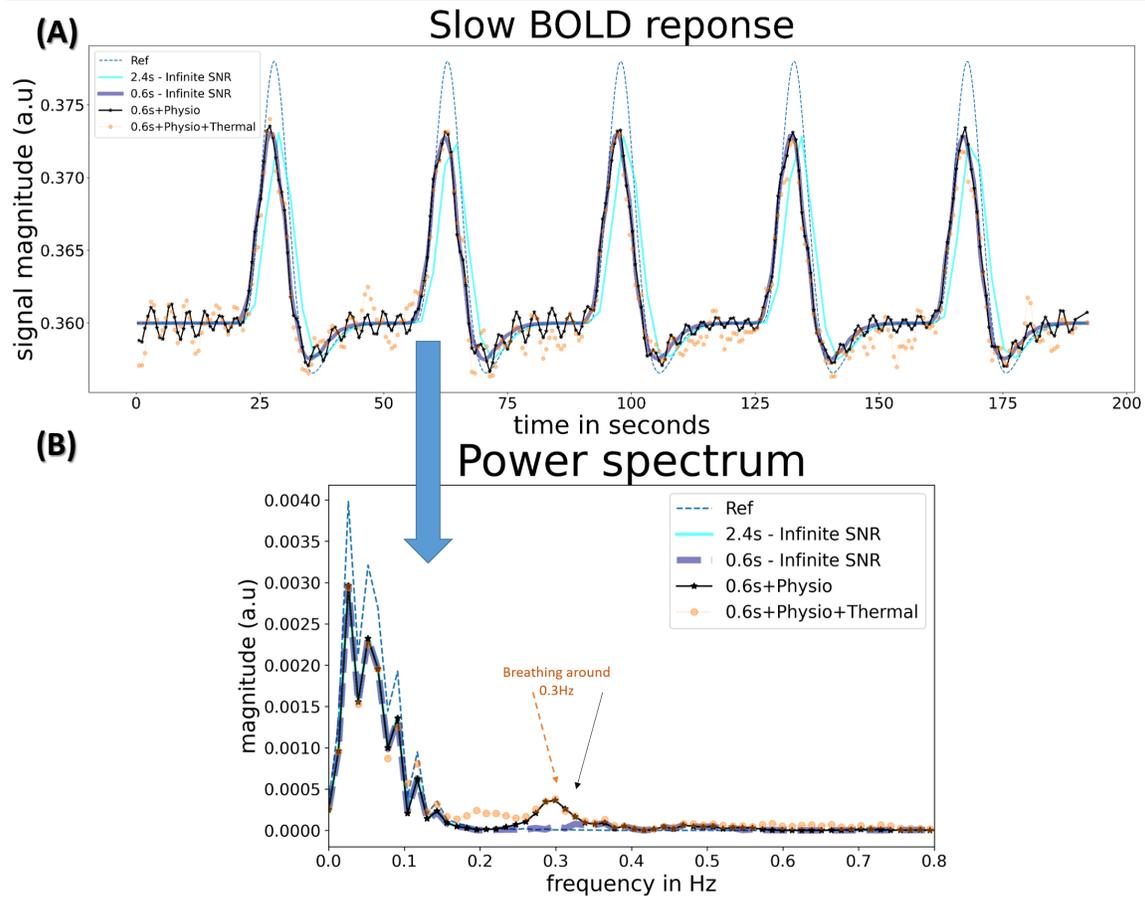


Figure 4: (A) Time courses in a single activated voxel, and (B) corresponding power spectra of a reference slow BOLD response vs. those estimated from simulated data (assuming an infinite SNR and accounting for physiological and/or thermal noises [SNR=100]) using a sequential (resp., sliding-window) reconstruction at a $TR_{native} = 2.4s$ (resp., $TR_{eff} = 0.6s$).

76 7 Conclusion

77 This simulation-based work demonstrates that a sliding-window reconstruction method allows for the
 78 tracking of BOLD oscillations beyond 0.2Hz and disentangle physiological noise from neural activity
 79 at realistic SNR/tSNR in 2D. Such a strategy can be extended to 3D imaging in a straightforward
 80 manner, thereby making whole-brain high spatiotemporal resolution fMRI feasible.

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