A REAL-TIME CARDIAC SYNCHRONIZATION METHOD FOR REDUCING FLOW-INDUCED INSTABILITIES IN SSFP FMRI OF THE BRAINSTEM

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Introduction The brainstem is a central structure for a range of cognitive and sensory systems, making it a compelling target for FMRI. However, the brainstem's small nuclei are particularly difficult to image due to intense local susceptibility artefacts (distortion and dropout). The brainstem also suffers from strong physiological noise fluctuations. Steady-state free-precession (SSFP) FMRI is highly compatible with short multi-shot 3D readouts, and thus has low distortion. SSFP has further been suggested to reduce sensitivity to physiological noise in cortical regions for 3D scans [1]. However, preliminary 3D data showed *increased* temporal instabilities in the brainstem compared to 2D acquisitions due to fluctuations that correlate with the cardiac cycle. We have previously presented simulations, which suggest that synchronizing the order of the k-space acquisition to the cardiac cycle should improve temporal stability [2]. We have also proposed a real-time feedback structure for achieving cardiac synchronization [3]. In the current work, we present a full working prototype system that achieves real-time cardiac synchronization without varying frame rate, based on GRAPPA and partial-Fourier reconstruction of corrupted data frames. This method significantly improves temporal stability in the brainstem.

Methods Pulsatile flow of blood and CSF introduce phase offsets to the magnetization. In multi-shot readouts, this translates into abrupt signal variation across k-space, causing time-varying ghosts and blurring of blood and CSF signal into adjacent tissue. In order to reduce flow-induced artifacts, one can synchronize the readout order to the cardiac cycle to create a smooth function across k-space (known as the COPE method) [4]. Ideally, each k-space segment would be acquired at a precise cardiac phase, but this cannot be ensured for all segments without varying the volume frame rate (Fig 2a), which can be problematic for FMRI paradigms and/or analysis. In the proposed method we aim to maintain a fixed frame rate while still achieving smooth k-space modulation. To determine the readout order in real-time, cardiac waveforms are acquired during the acquisition and fed back into the sequence by using a pulse oximeter. If no suitable k-space segment is available to be acquired, we designate one segment to be omitted (left blank). This missing data is then estimated using GRAPPA reconstruction (Fig 1c, method 1) [5]. The synchronisation method places data from peak systole (which has greatest fluctuation) at one edge of k-space. A second optimization is thus to replace this data using POCS partial-Fourier reconstruction [6] (Fig 1c, method 2).

Experiments Passband SSFP data were acquired in 4 healthy volunteers on a 3T Siemens Trio scanner (Siemens, Erlangen) using a 12-channel head coil. 3D time-series were acquired with and without the proposed real-time cardiac synchronized readout. Scan parameters were as follows: α=30°, TR/TE=12/6 ms, FOV=192x192x48, Matrix=96x96x24, 1860 Hz/px, 8 lines per TR, Tvol=3.5s, 60 volumes. The shim volume was targeted over the brainstem. For the synchronized data, on average 15% of the segments could not be acquired at the correct cardiac phase and were estimated using a 3D GRAPPA kernel. In addition to a reconstruction using the full extent of k-space (method 1), a 5/6 POCS Partial Fourier reconstruction was also performed, to discard the frames acquired during systole (method 2).

Results Cardiac synchronization improves the temporal signal-to-noise ratio (tSNR) in the brainstem considerably. Fig. 2 shows typical results in one subject of data acquired with and without synchronization. ROI analysis reveals an average increase in brainstem tSNR of 49% (table 1). In cortical grey matter (cGM) the tSNR is slightly reduced (-7%), which may partly be caused the loss of SNR associated with dropping data frames. Although method 1 and method 2 visually appear to show similar improvements, ROI analysis shows that Partial Fourier reconstruction (method 2) has slightly lower tSNR than synchronization only (method 1) in both the brainstem and cGM. Simulations suggested that removal of data acquired during systole would increase the stability. Unfortunately the improvement is not sufficient to counteract the drop in SNR inherent to partial Fourier.

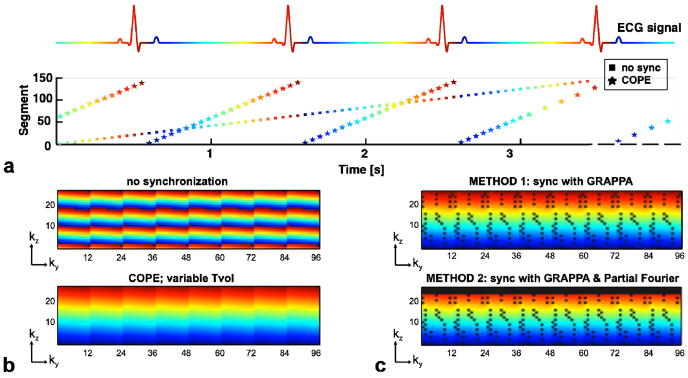

Figure 1: synchronization method a) the order in which the segments are acquired with and without synchronization. b) ky-kz views of the readout in which the colours denote the point in the cardiac cycle at which each readout line is acquired. Left: without synchronization and with perfect synchronization. Right: the two proposed synchronization methods. Grey denotes discarded data.

Discussion Synchronization reduces the effects of cardiac pulsatility by creating a smooth modulation across k-space. However, the respiratory function (which is normally a smooth k-space modulation) would become scrambled by reordering of the acquisition. This potentially amplifies any respiration-induced instabilities of SSFP due to the sensitivity to B_0 fluctuations. The tradeoff of reduced cardiac sensitivity for higher respiratory sensitivity is clearly beneficial in the brainstem, but could degrade signal in the cortical areas that are less affected by cardiac related instabilities. The real-time B_0 respiratory correction described by Lee *et al.* [7] could mitigate these effects and is fully-compatible with our method. The cortical regions have high overall tSNR in SSFP data and thus a small reduction in tSNR may be an acceptable compromise for improved brainstem stability.

References. [1] Miller et al. NIMG 2007 [2] Tijssen et al. ISMRM 2010 [3] Tijssen et al. HBM 2010 [4] Cho. MRI 1990 [5] Griswold et al. MRM 2002 [6] Lindskog et el. JMRI 1991 [7] Lee et al. MRM 2006

Table 1: ROI analysis. tSNR in brainstem and grey matter in four subjects

Subject	Brainstem			Cortical grey matter		
	no sync	sync	sync & PF	no sync	sync	sync &PF
1	16	22 (+42%)	20 (+30%)	34	33 (-3%)	32 (-7%)
2	14	19 (+38%)	19 (+35%)	37	34 (-9%)	32 (-13%)
3	10	17 (+73%)	17 (+67%)	35	32 (-8%)	31 (-11%)
4	15	22 (+43%)	21 (+35%)	34	31 (-9%)	29 (-13%)
mean	**14**	**20** (+49%)	**19** (+42%)	**35**	**33** (-7%)	**31** (-11%)

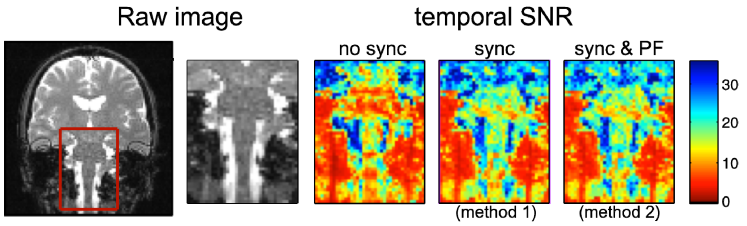

Figure 2: results. RAW SSFP image showing the centre slice (left) with tSNR maps of the data acquired with and without cardiac synchronization. The zoomed windows show a considerable increase in tSNR in the brainstem when synchronization is performed