# High temporal resolution, simultaneous quantification of intravascular blood flow and oxygen saturation with BRISK k-space sampling

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**INTRODUCTION:** Partial k-space updating strategies, including keyhole and projection-based imaging, allow for rapid, simultaneous quantification of intravascular blood flow and oxygen saturation. Such techniques have been used to quantify the cerebral metabolic rate of oxygen consumption ($CMRO_2$) in response to physiologic stimuli[1] and to characterize the severity of peripheral artery disease in a femoral occlusion-reperfusion model of reactive hyperemia.[2] Because these strategies assume dynamic information is bandlimited in k-space, they are not robust against motion and will tend to bias toward the reference data containing the outer k-space information. This is of particular concern in imaging studies in which stillness is difficult due to the length of the scan, the nature of the paradigm, or subject compliance, or when significant physiologic changes occur. BRISK k-space sampling,[3] which updates outer k-space segments at decreasing frequency, has the potential to address these limitations while preserving temporal resolution.

**METHODS:** A dual-echo phase contrast pulse sequence for rapid, simultaneous quantification of blood flow and blood oxygen saturation (OxFlow) was developed (**Fig. 1a**). Blood flow is quantified from the phase difference between images generated at echo 1 with toggled first gradient moment. Blood oxygen saturation ($\%HbO_2$) is quantified by modeling the vessel of interest as a long paramagnetic cylinder and measuring the phase accumulation of the intravascular signal between images generated at echoes 1&2.[4,5] Sequence parameters are: flip angle 15°, dwell time 15 μs, TE/ΔTE/TR 5.2/7.04/19.2 ms, venc 50 m/s, matrix 208×208x1, resolution 0.85×0.85×5mm.

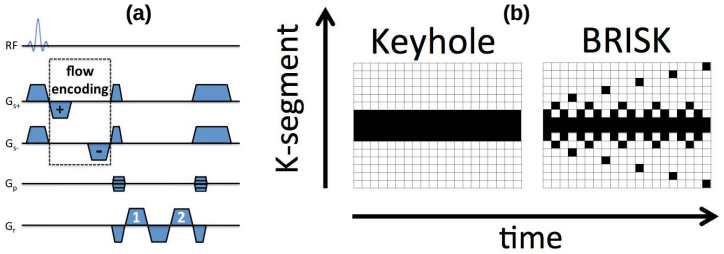


**Figure 1: (a)** dual-echo OxFlow pulse sequence for simultaneous flow and $\%HbO_2$ quantification; **(b)** schematic of BRISK and keyhole k-space sampling strategies

*K-space sampling* -- BRISK and keyhole versions of the OxFlow sequence were developed, both with phase encode reduction factors of 4 yielding a temporal resolution of 2 s. In BRISK sampling (**Fig. 1b**), images are reconstructed by interpolating across time points using the nearest (most recent or future) acquired data at each k-segment, effectively resulting in a sliding window reconstruction with a minimum width of 2 s for the inner 1/8$^{th}$ of k-space and 40 s for the outer half of k-space. In keyhole (**Fig. 1b**), the inner 1/4$^{th}$ of k-space is continuously updated, with outer k-space supplied from fully sampled reference images acquired at the beginning and end of the scan.

*In Vivo Experiments* -- To evaluate the sampling strategies, three experiments were conducted in a healthy 27 y/o male volunteer: 1) a motion paradigm with the subject asked to shift his head 1 min into a 2 min acquisition, repeated with BRISK and keyhole sampling at the level of the superior sagittal sinus (SSS), 2) a breath hold paradigm involving two 80 s breath holds, repeated with BRISK and full sampling at the SSS, and 3) a reactive hyperemia paradigm with an inflatable pressure cuff used to occlude femoral blood flow for four minutes before being released, repeated with BRISK and full sampling at the femoral vessels inferior to the cuff. All experiments were performed on a 3T Siemens Trio scanner with an 8 ch. head or 8 ch. knee coil.

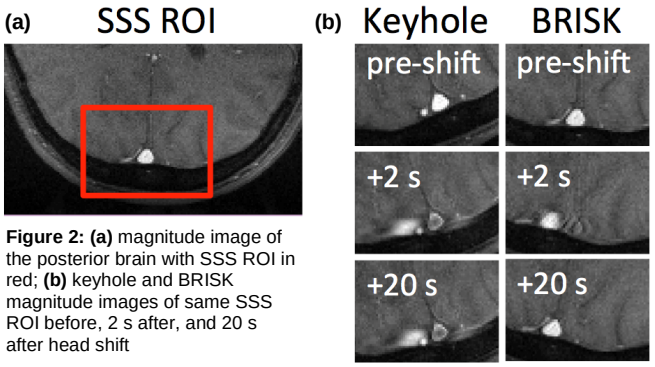


**Figure 2: (a)** magnitude image of the posterior brain with SSS ROI in red; **(b)** keyhole and BRISK magnitude images of same SSS ROI before, 2 s after, and 20 s after head shift

**RESULTS: Fig. 2** shows images of the SSS immediately before, 2 s after, and 20 s after head shift, using keyhole or BRISK k-space sampling. **Fig. 3** shows SSS flow and $SvO_2$ values during breath hold (**3a**) or reactive hyperemia (**3b**) with data from BRISK and full k-space acquisitions displayed together.

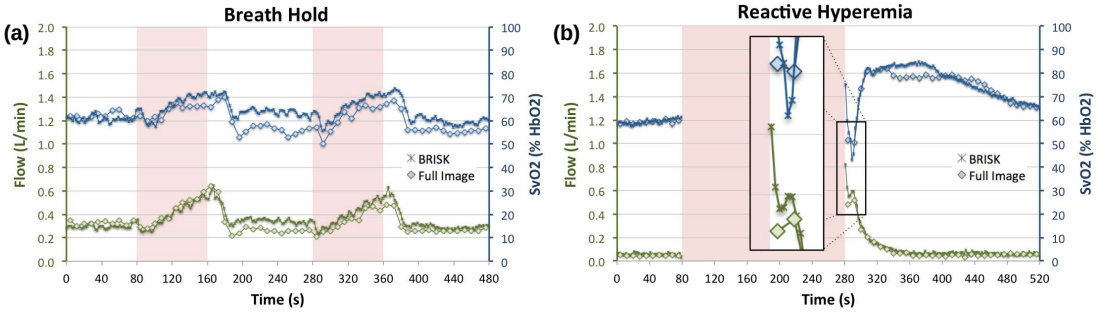


**Figure 3:** flow and $SvO_2$ curves for BRISK and full k-space sampling in response to **(a)** breath hold and **(b)** reactive hyperemia with red shading indicating periods of **(a)** breath hold or **(b)** cuff inflation

**DISCUSSION:** In Fig. 2, the motion artifact persists in all post-shift keyhole images but quickly resolves in the BRISK images, demonstrating the reduced motion sensitivity of BRISK. In Fig. 3a, flow and $SvO_2$ increase in response to the hypercapnia and hypoxia that develop during breath hold. In Fig. 3b, the reactive hyperemic response is characterized by a rapid increase in blood flow, causing first a washout of deoxygenated blood followed by a persistent decrease in oxygen extraction. The improved temporal resolution of BRISK results in better resolution of these dynamic physiologic changes compared to full k-space acquisition, especially evident by the sharper peaks in the BRISK acquisition in Fig. 3b, shown in magnification.

**CONCLUSIONS:** The data presented suggest BRISK k-space sampling applied to a dynamic OxFlow pulse sequence to be advantageous, allowing a 4x improved temporal resolution compared to full k-space acquisition with less motion sensitivity than keyhole. In ongoing studies, this technique is being used to measure $CMRO_2$ in response to an intermittent apnea paradigm in subjects with obstructive sleep apnea (OSA), with the goal of characterizing OSA disease progression and treatment response and better understanding the basis of OSA-associated neurologic pathology.

**REFERENCES:** [1] Rodgers, et al., *ISMRM* 2012. [2] Langham and Wehrli, *JCMR* 13:66 (2010); [3] Doyle, et al., MRM 33:163-170 (1995); [4] Haacke et al., *Hum. Brain Map* 5:341-6 (1997); [5] Fernandez-Seara et al., *MRM* 55:967-73 (2006); **Grant Support: NIH R21-HD069390 / T32-EB000814.**