Rapid multi-shot segmented EPI using the Simultaneous Multi-Slice acquisition method

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Introduction: Highly-accelerated imaging allows for rapid single-shot EPI acquisitions to mitigate the distortion and blurring effects seen at high magnetic field strengths, however there is an intrinsic SNR penalty that scales with the square-root of the acceleration factor and with the g-factor, ultimately limiting its usability. Multi-shot segmented EPI acquisitions can similarly mitigate these deleterious effects, yet the longer temporal sampling interval amplifies physiological noise and system instabilities. Recently, Simultaneous Multi-Slice (SMS) techniques have been demonstrated for increasing temporal resolution in fMRI by factors of three and higher without the $\sqrt{R}$ penalty [1-5]. In fact, these techniques are so successful they provide temporal resolutions above what is needed for sampling the hemodynamic response [2]. In this case, it might be beneficial to use the SMS method (with its lack of a $\sqrt{R}$ penalty) in conjunction with multi-shot imaging (also lacking the $\sqrt{R}$ penalty) and rely less on in-plane acceleration for distortion mitigation in high-resolution fMRI. Thus, we merge a segmented multi-shot EPI acquisition with the SMS technique retaining a conventional 2-3 s temporal sampling interval. This combination of techniques allows each EPI segment to employ a distinct multi-slice excitation pulse similar to that used in the CAIPIRINHA technique, enabling advantageous slice-aliasing patterns to reduce the g-factor of the SMS reconstruction [5]. This eliminates the need for a *z* gradient blip scheme [3,4], which achieves the same end.

Methods: Two subjects were studied with a whole-body 3T Tim Trio MRI scanner (Siemens Healthcare, Erlangen, Germany) with the vendor supplied 32-channel head array. The acquisitions were 1.5×1.5×2 mm^3 gradient-echo EPI with TR/TE/fa/matrix/BW/esp = 2.7 s/30 ms/90°/128×128/1502 Hx/px/0.75 ms, with 60 timepoints, and 39 slices. We employed an SMS factor of 3 such that each pulse excited 3 slices, yielding a gap between collapsed slices of 2.6 cm, and reducing the TR from and 2.7 s to 0.9 s. (Note that, due to the two shots, the "time per image" was 1.8 s.) A distinct pulse was designed and used for each of the two segments: the first segment's pulse was a concatenation of three identical slice-selective pulses, whereas the second segment's pulse imposed a positive phase on the center slice and a negative phase on the two side slices, similar to a Hadamard pulse design [6]. To compensate for the increased SAR in these concatenated pulses, the pulses were designed with the VERSE method [7] to reduce the maximum voltage by a factor of 2. To maximize image SNR, the flip angles were adjusted to Ernst angle of 70°. For comparison, we acquired a distortion-matched R=2 accelerated, GRAPPA reconstructed EPI data without SMS. All images were reconstructed offline, and the slice-GRAPPA method [3,4] was used to separate the collapsed slices in the SMS data. To evaluate the physiological noise contamination imposed by the segmented readout, we calculated time-series SNR for all acquisitions.

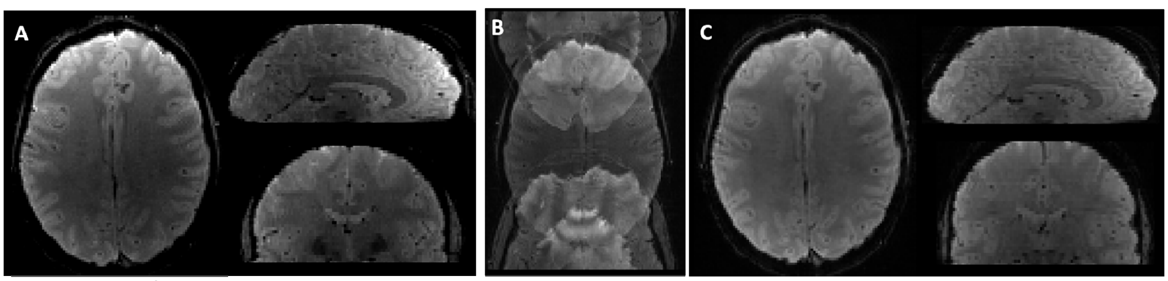

Fig. 1: Example images of (A) conventional 1.5×1.5×2 mm two-shot EPI acquisition with online reconstruction, (B) raw collapsed images from the proposed method prior to image reconstruction, and (C) the final images after application of the slice-GRAPPA reconstruction.

Results: The resulting multi-shot SMS images are shown in Fig. 1. The slice-GRAPPA method successfully separated the collapsed slices with little if any residual artifact. Instabilities can be seen in the time series data, which is expected when using multi-shot techniques. A comparison of the resulting time-series SNR across the acquisitions is shown in Fig. 2. As expected, the segmented acquisition results in some structured pattern reflecting time-series variability likely due to physiological fluctuations occurring between each acquired segment, but overall the SNR between the two acquisitions is comparable.

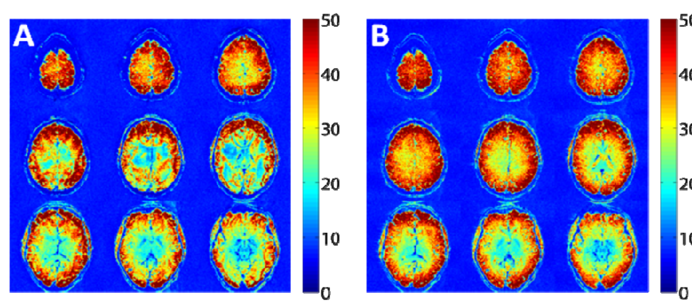

Fig. 2: Time-series SNR maps for the single-shot and SMS multi-shot acquisitions. (A) SMS factor 3, 2-shot tSNR, (B) single-shot R=2 tSNR.

Discussion: The use of two segments enabled a straightforward application of a FOV/2 shift of the collapsed slices, similar to the original CAIPIRINHA method [5], obviating the need for additional gradient blips in the *z* direction to impose this shift [3,4]. However, to extend this framework to more segments and a larger number of shots, *z* gradient blips can readily be included to achieve the necessary image shift. In future work we will explore EPI techniques for reducing the physiological noise contamination and incorporate these into the SMS framework, including online correction of dynamic changes in off-resonance due to respiration [8] and alternate methods for segmenting the EPI readout [9].

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