Characterization and Mitigation of Signal Leakage in Simultaneous Multi-Slice (SMS) Acquisition

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Target audience: Functional and Diffusion MR Imaging investigators

Purpose: Simultaneous Multi-Slice (SMS) acquisition (1-5) with blipped-CAIPI scheme (6) has enabled dramatic reduction in imaging time for fMRI and Diffusion imaging. The signal leakage (7,8) is an important metric that characterizes signal corruption (due to leakage of signal from one slice to another) for such an acquisition. Here, we show that the two methods for calculating signal leakage; the method introduced by Moeller which we term Frequency Modulation/Monte Carlo (FMMC) (7) and the Linear System Leakage Approach (LSLA) (8) are related, and illustrate why LSLA might result in a more general leakage metric that can be rapidly computed. Additionally, we propose and demonstrate two techniques to modify the slice-GRAPPA (SG) reconstruction to achieve dramatic reduction in signal leakage.

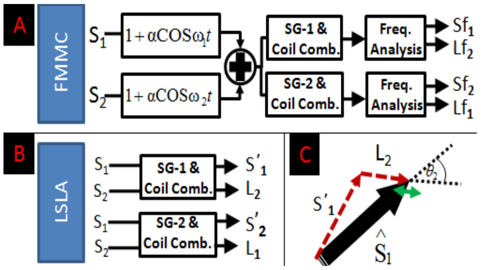

Fig 1: Leakage calculation diagrams for FMMC & LSLA.

Theory: *Leakage calculation:* Fig. 1A shows the FMMC leakage calculation(7). Here, the signals of slices 1 and 2 (S_1&S_2) are used to generate slice-aliased time-series data with an imposed slice-dependent sinusoidal modulation in time. The data in this time series is then slice-unaliased (SG-1 and SG-2 represents SG for slice 1 & 2) and processed through the coil combination process. Frequency analysis is performed on the unaliased data to obtain the pass-through and leakage signal components (Sf &Lf). Fig. 1B shows the LSLA calculation as proposed in (8). Here, the signals from all slices are individually passed through the SG reconstruction of each slice to create the pass-through and leakage signal (S'&L). LSLA utilizes the fact that SG reconstruction is a linear operation to allow each component of the slice-aliased signal to be analyzed separately, thereby bypassing the time-consuming time series/frequency component analysis of FMMC. However, the pass-through and leakage signal calculated by the two methods are not identical—but are related. Their relationship can be understood by the diagram in Fig 1C. Using results from LSLA, the estimate of slice 1 signal from the slice-collapsed data via SG reconstruction ($\hat{s}_1$) is created by combining the pass-through and leakage signal components. In FMMC, a small sinusoidal modulation of amplitude α is imposed on S_2. This would create a modulation of amplitude αL_2 on the leakage signal (green arrow) parallel to L_2, which in turn causes a modulation of $\alpha L_2 \cos(\theta_2)$ on the $\hat{s}_1$ signal, where θ_2 is the relative phase between L_2 and $\hat{s}_1$. Based on this, the leakage calculated using Method 1 and 2 are related by $Lf_2 = L_2 \cos(\theta_2)$ (Both methods were implemented and this relationship was verified). This informs us that the leakage from FMMC is dependent on the relative phase between S_1 and S_2. In fMRI acquisitions, spatially varying phase evolution can occur due to drift, cardiac/respiratory changes, and fMRI activation, while in diffusion imaging, small amounts of tissue motion can lead to dramatic phase changes. The leakage calculated from LSLA does not depend on the relative phase between the slice's signal and thereby provides a less biased metric. *Modified SG reconstruction:* With standard SG (6) (Std-SG), the kernels are calculated by solving: $\arg\min_{k_i} \|S_i - [A_{sc}]k_i\|_2$ [eq.1], where S_i and k_i are vectors of k-space signal and GRAPPA kernel for slice *i*, and $[A_{sc}]$ is the slice-collapsed convolution matrix. This optimization aims to find a kernel set that best estimates slice *i* from the collapsed data. However, the matrix $[A_{sc}]$ contains signal from all slices, and so it is possible that the signal from slices other than slice *i* will be used to help estimate S_i; leading to signal leakage. It was previously shown (6) that typical aliased imaging slices tend to have different enough image contrast, such that this signal leakage contribution is small. Nonetheless, at high slice-acceleration factors this may not hold, leading to significant leakage signal. In this work, we propose two methods to address this issue. (i) Random Phase SG (RP-SG): here, differences in the slice image contrast are artificially boosted during the kernel optimization by adding a distinct spatially-varying random phase pattern to the image signal of each of the imaging slice training data prior to performing the kernel calculation via [eq.1]. (ii) Split SG (Sp-SG): with this method, the following optimization is used to calculate the GRAPPA kernels: $\arg\min_{k_i} \|S_i - [A_i]k_i\|_2 + \lambda\sum_{j\neq i} \|[A_j]k_i\|_2$ [eq.2], where A_i is slice *i* convolution matrix. Here, [eq.2] aims to find a kernel set that best matches the pass-through signal with the underlying signal, while minimizing the leakage signal.

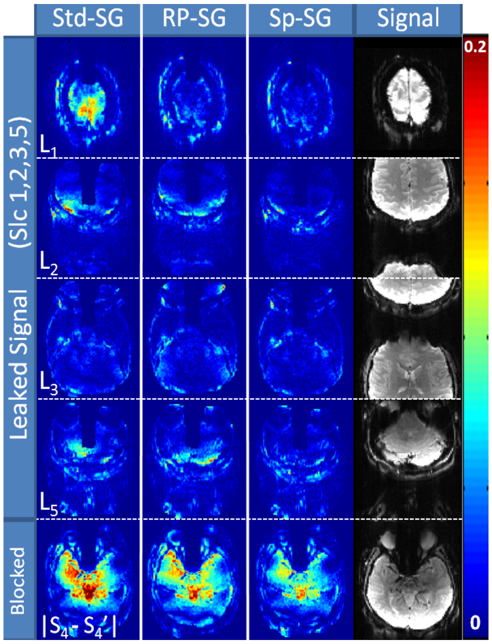

Fig 2: leakage and blocked signal for slice 4 from SMS5 acquisition using three variants of SG reconstruction.

Methods: To assess the performance of the various SG methods, unaccelerated multi-slice GRE-EPI data (FOV: 208×208×120 mm^3, 2mm isotropic voxel size) were acquired on a Tim Trio 3T scanner (Siemens Healthcare, Germany). Using this data, simulations were performed to synthesize an SMS dataset with slice-acceleration factor of 5 and blipped-CAIPI FOV/3 shift. Leakage signal (L), blocked signal (S-S') and g-factor penalty were calculated for the various SG methods.

Results: Fig. 2 shows the leakage and blocked signal of slice 4 in SMS5 data from the Std-SG, RP-SG, and Sp-SG reconstructions. The underlying signal images in their relative shifted positions are also shown. The mean and maximum leakage (L-factor) for the three reconstruction methods were 0.023, 0.018, 0.015 and 0.24,0.15, 0.15, respectively, while the mean blocked signal was 0.068, 0.064, 0.05. Significant reduction in leakage artifact was achieved by RP-SG and Sp-SG methods, with the most reduction coming from Sp-SG, (35% and 38% reduction in mean and max leakage). The blocked signal was also reduced, which indicates a better fidelity in representing the underlying signal from a particular slice. The g-factor maps for the three reconstructions were nearly identical (not shown) with 1/g-factors (mean +/– std) values of 0.9702+/–0.8, 0.96+/–0.085, 0.94+/–0.085. **Conclusion:** Signal leakage is an important measure in characterizing signal corruption for SMS acquisition. In this work, we demonstrate a technique that can be used to rapidly compute signal leakage metrics, and demonstrate two techniques to modifying the slice-GRAPPA (SG) reconstruction to significantly reduce leakage artifact without affecting the g-factor penalty.

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