Signal Leakage(L-factor) as a measure for parallel imaging performance among simultaneously multi-Slice (SMS) excited and acquired signals

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Introduction Parallel imaging methods have significantly improved the temporal efficiency of many applications in MRI. The geometry (g) factor has been widely utilized to quantify noise amplification and subsequent SNR losses in PI methods arising from the limited ability of coil sensitivity profiles to un-alias signals. However, the g-factor does not account for potential artifacts due to residual aliasing in un-aliased images. At 3T, using typical resolutions, a limited amount of in-plane under-sampling, if any, is used in EPI-based acquisitions since tradeoffs in reducing readout times, TR, etc., do not warrant much acceleration, especially given modern high performing gradients. This, coupled with high coil counts, has made residual aliasing less concerning. However, recently we demonstrated the possibility and utility of extremely high accelerations for EPI-based fMRI and diffusion imaging based on simultaneous slice excitations [1-2]. By exciting multiple slices simultaneously, we are able to concurrently reduce the volume TR in a 2D acquisition, and as many fewer excitations and encodings are needed. This TR reduction increased fMRI sensitivity and permitted significant reductions in diffusion scan times [2] as multiple slices share diffusion encoding gradients. The benefits from volume TR reductions become even more significant when higher spatial resolutions (i.e. more slices) are used. As such, even higher slice accelerations could be beneficial, making effects due to residual aliasing a concern. These effects could result in spatially mis-mapped activations (or i.e. spurious fibers throughout the brain) due to signal leakage in simultaneously acquired slices. To address this concern, we describe here a new metric, the (leakage) L-factor, to quantify these effects and propose that both l-factors and conventional g-factors should be considered in highly accelerated acquisitions.

Methods Multi-slice GRE-EPI data (FOV: 192 x192 mm^2, 2mm isotropic) were acquired on a 3 Tesla Siemens Skyra (Siemens, Erlangen, Germany) scanner equipped with SC72 gradients, a body transmitter and a 32-channel head receiver coil. Multiband separation was performed using a coil-by-coil data driven (CCDD) algorithm [5]. It consists of a series of linear matrix multiplications projecting the aliased signal (MB(k)) onto distinct signals related to separate slices (Sn) in a coil-by-coil process. G-factor noise amplification is calculated using the Monte-Carlo [6] method, where the change in noise-distribution is used as a measure of noise-degeneration due to slice-separation. L-factor quantification (described below) is calculated using un-accelerated (single band) EPI data. Subsequently, simulated multiband data are generated offline by adding signals from multiple slices using a variety of different pseudo (simultaneous slice) accelerations and controlled aliasing schemes [3-4]. Prior to simulating a multiband acquisition and subsequent slice unaliasing, a unique slice specific temporal modulation was globally imposed on each slice (simulating i.e. an fMRI signal modulation). From a single band multi-slice acquisition, a multiband time series with M frames can be formed such that:
$MB(k,t) = \sum_{slice} \alpha(slice,t) SB_{slice}(k)$ where, $\alpha(slice,t) = (1 + 0.1 * \cos(4\pi \cdot slice \cdot t)), t = 0 \cdots (M-1)$. Designate by $S_{slice}^{recon}(x,t)$ the reconstruction of $MB(k,t)$ into distinct slices. The frequency response of $\alpha(slice,t)$ is uniquely defined for each slice; denoted with f_{slice}, slice={1,..,N}. For the formulated MB time series, signal leaking from a given slice to all others is determined from $S_{slice}^{recon}(x,f)$ for $f \neq \{f_{slice}\}$ (i.e. residual energy at imposed frequencies of other slices). To obtain comparable coefficients, $S_{slice}^{recon}(x,f)$ is normalized for each f subject to $\sum_x |S_{slice}^{recon}(x,f_{slice})| \equiv 1$. Signal leakage is calculated as the L-factor, for each slice, as $L-factor(slice',slice) = \mu(slice') \sum_x |S_{slice'}^{recon}(x,f_{slice})|$, but masked to only include pixels in the brain (defined with a threshold ε) and $\mu^{-1}(slice') = \sum_x \left(\left|S_{slice'}^{recon}(x,0)\right| > \varepsilon\right)$. The average L-factor is defined as $mean_{slice' \neq slice}\{L-factor(slice',slice)\}$, i.e. as the average of all combinations.

Results. Histograms of g-factors for a whole brain acquisition for 4 different simulated slice-accelerations are shown in figure 1, where a ¼ shift of the FOV between adjacent slices is imposed [3-4]. At high accelerations, the mean g-factor plateaus, suggesting limited information about image fidelity using this measure. On the other hand, normalized L-factor (leakage) images, shown in figure 2, depict signal leakage in cases where g-factor noise is modest. The MB simulation in the top row, as in [1-2], does not use controlled aliasing [7], while the bottom row does [3-4]. The average L-factors for different MB factors (with (PE4) and without (PE=0) controlled aliasing) are listed in table 1. In our recent work [2], we demonstrated robust and reliable detection of resting state networks (i.e. without significant detectable artifacts) using similar methods. Given those results, as an approximate guide, one can consider mean L factors ~0.05 or less as acceptable. Apparent in both the L-factor image and mean values, the use of a blipped based controlled aliasing scheme for EPI [3-4] significantly reduces signal leakage permitting much higher slice accelerations.

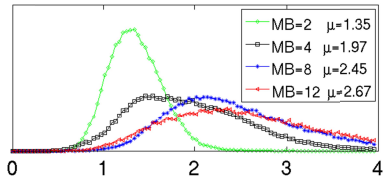

Fig.1 G-factors for different MB factors using controlled aliasing.

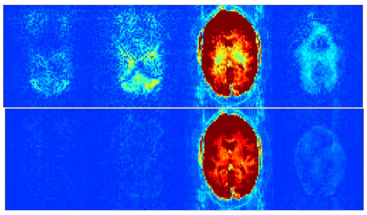
Fig.2 Signal leakage images from 4 simultaneous slices with (bottom) and without (top) controlled aliasing.

MB	2	3	4	6	8	10	11	12
PE=0	.01	.03	.08	.14	.20	.25	.32	.32
PE=4	.01	.01	.02	.03	.03	.04	.06	.07

Table 1. Mean L-factors for different MB factors with (PE=4) and without (PE=0) controlled aliasing.

Conclusions. The L-factor, proposed as a new metric to quantify residual aliasing in acceleration imaging, should be considered in addition to g-factors when planning an experiment. For high accelerations, recently made possible by improved coil designs, pulse sequence developments (controlled aliasing) [3-4], and optimized image reconstructions, knowledge of g-factor noise amplification alone is insufficient. Signal artifacts due to residual aliasing, as described by the L-factor, can be quantified for any arbitrary multi-channel coil configuration, slice acceleration, orientation, and separation and can give critical information about image integrity. Future work will aim to correlate L-factor levels with a defined amount of artifact level (i.e. in a real fMRI experiment) using similar methods.

Reference [1] Moeller, et al. *Magn. Reson. Med.* 63:1144–53, 2010 [2] Feinberg, et al. PLoS ONE, 5(12):e15710, 2010 [3] Setsompop, et al. *Magn. Reson. Med.* 2011 [4] Xu et al ISMRM 2012 [5] Brau et al, *Magn. Reson. Med.* 59:382-395, 2008 [6] Robson et al, *Magn. Reson. Med.* 60(4):895-907, 2008 [7] Breuer, et al. *Magn. Reson. Med.* 53:684–91, 2005

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