SALSAS: Spectral Spatial Excitation Combined with Z-Shimming to Mitigate Through-Plane Signal Loss in Single-Slice and Multiband Gradient Echo Imaging

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Target Audience Researchers interested in image artifact and signal loss correction in long-echo time MRI scans.

Introduction Long echo time (TE) multislice scans such as BOLD fMRI and susceptibility-weighted imaging suffer signal loss artifacts near air-tissue interfaces, e.g. frontal sinuses, due to magnetic susceptibility differences. These susceptibility differences give rise to through-slice off-resonance gradients that cause the excited spins to dephase with respect to each other, leading to signal cancelation at readout. To correct these artifacts the z-shim method[1] was proposed, wherein a gradient waveform is played in the slice direction to cancel phase accrued due to the off-resonance at TE. Multiple images are acquired with different *z*-gradient areas/shims to refocus different regions, and the images are combined to form one image with no signal loss. However, a significant drawback to the method is that the shimmed images must be acquired in separate TRs to maintain full signal, since the entire slice is excited for each shim measurement. In this work we propose an approach called SALSAS (SpectrAL SpAtial z-Shim) that uses spectral-spatial[2] (SPSP) excitation pulses to selectively excite only the regions of the brain that will be refocused by the z-shim. This allows the z-shim acquisitions to be treated simply as additional slices in a multi-slice stack, minimizing scan time penalty. The method is also compatible with simultaneous multislice acquisitions[3]. Compared to previous multidimensional excitation approaches to mitigate through-slice signal loss[4,5,6], the method does not require sophisticated multidimensional and subject-tailored RF pulse designs, and can use sharper slice profiles.

Theory It has recently been shown that there is a spatial correlation between mean off-resonance frequency in a 2D image voxel, and the through-slice off-resonance gradient in that voxel[4]. The proposed method exploits this observation by using SPSP pulses to excite regions with specific field gradients by centering the pulses' passbands to target the corresponding mean off-resonance frequency. The excited spins can then be rephased by playing a z-shim gradient. Unlike conventional z-shim, these acquisitions can be performed directly after each other without SNR penalty, since only the shimmed region is excited. Figure 1 illustrates the method in comparison to conventional z-shim. SALSAS can also be used in simultaneous multislice acquisitions by replacing the slice-selective SPSP subpulses with multiband subpulses.

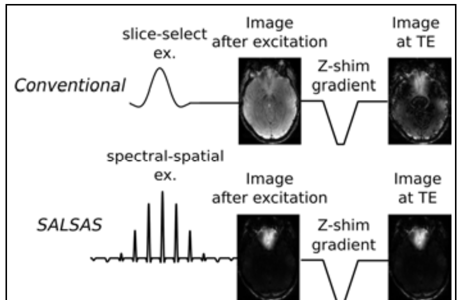


Figure 1: Illustration of SALSAS method. Unlike conventional Z-shim, SALSAS selectively excites and rephases only the region to be shimmed.

Methods Phantom experiments were performed using a head volume coil on Philips Achieva 7T scanner (Philips Healthcare, Cleveland, OH). To simulate magnetic susceptibility differences, a 1 cm staple was taped on a spherical Agar gel phantom. B_0 maps were measured over a 20 cm FOV with a 64x64 matrix size to identify SPSP passbands. Two SPSP pulses were designed: one to excite the region distorted by the staple, and another to excite rest of the slice. The strength of the z-shim gradient for the distorted region was manually tuned to maximize signal. SALSAS and conventional z-shim images were acquired using a modified multi-slice spin warp gradient echo sequence (TR/TE 150/25 ms) wherein the two shims were treated as adjacent slices and acquired directly after each other. The same *z*-shim was used for SALSAS and conventional z-shim. In another multiband phantom experiment, conventional and spectral-spatial multiband pulses were designed to excite three slices at -2, 0 and +2 cm from isocenter. The *z*-shim area was selected to rephase the slice at isocenter. A 3D gradient echo readout was used to image the excitation pattern over a 20x20x19 cm FOV and matrix size 224x224x38. To validate the method in vivo, human experiments were performed on Philips Achieva 3T scanner (Philips Healthcare, Best, Netherlands). Two SPSP pulses with spectral time-bandwidth of 3 and spatial time-bandwidth 4 were designed to excite the orbitofrontal cortex and the rest of the brain, respectively. The pulse durations were 26.7 ms and 14.2 ms. 2D Gradient Echo images were acquired over a 26x26 cm FOV, 4 mm slice thickness, 256x256 matrix size and TR/TE of 750/25 ms.

Results and Discussion Figure 2 shows the results from the 7T phantom experiment. The combined gradient echo images show that SALSAS gave a peak signal 23% higher than conventional z-shim near the center of the phantom where the true flip angle is reached because the scanner sets the transmit gain such that spins at the center of the sample experience the target flip. The table compares the theoretically calculated percentage of gray matter (GM) (T_1 = 1.2 s at 3T and 2 s at 7T) longitudinal magnetization available after two conventional z-shim and SALSAS acquisitions performed back-to-back (as though in a multi-slice stack), with a 100 ms delay for acquisition of the first shim, and a 1 s overall TR. There is more longitudinal magnetization available to convert to MR signal at the end of SALSAS TR than conventional z-shim. Figure 3 shows the results from the multiband experiment. Both conventional z-shim and SALSAS excited the targeted slices. SALSAS was able to selectively excite and rephase the spins in 'region 2' in the targeted middle slice. But images from the conventional z-shim experiment show unwanted excitation outside the desired region in all the slices. 3T in vivo results in Fig. 4 show that SALSAS was able to selectively excite and rephase the spins in the targeted orbitofrontal cortex, whereas conventional z-shim shows unwanted excitation outside the target region.

Conclusion We have introduced a new, practical method to mitigate signal loss artifacts in long-echo time gradient echo scans, which is also capable of use with simultaneous multislice.

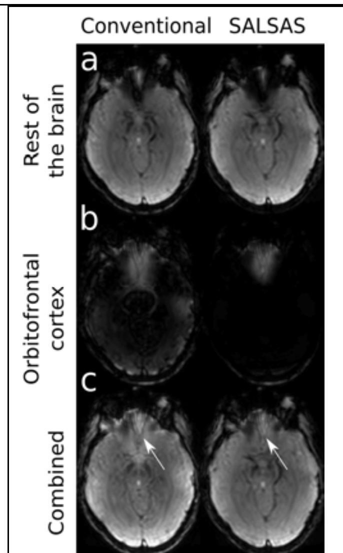
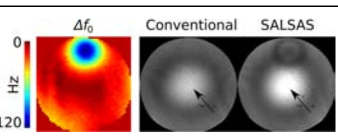


Figure 4: 3T in vivo results. SALSAS pulses selectively excite and rephase spins in the orbitofrontal cortex (b) and the rest of the brain (a). (c) The combined images show good overall signal recovery. Arrows point to recovered regions.



M_z	z-shim 1	z-shim 2	SALSAS
3T GM	61%	36%	72%
7T GM	45%	26%	56%

Figure 2: 7T phantom results. Arrows point to region where SALSAS gave 23% higher peak signal than conventional z-shim in multi-slice imaging. Table shows that more than 2x longitudinal magnetization is available at the end of SALSAS TR than z-shim.

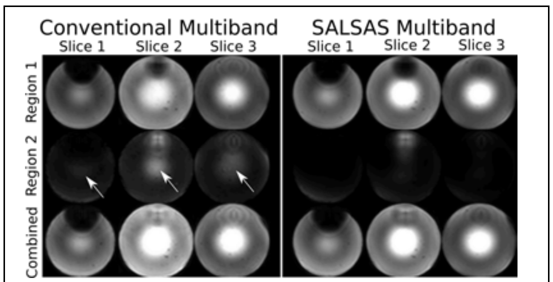


Figure 3: 7T multiband results. SALSAS correctly excited and rephased the targeted middle slice. Whereas, arrows in the conventional z-shim image point to unwanted excitation outside the desired region in all the slices.

Acknowledgements
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References [1] R.T. Constable, JMRI, 5(6), 1195. [2] C.H. Meyer, et al, MRM, 15:287-304, 1990. [3] D.J. Larkman et al, JMRI, 13:313-317, 2001. [4] C.Y. Yip et al, MRM, 61:1137-1147.2009 [5] C.Y. Yip et al, MRM, 56:1050-1059, 2006. [6] Stenger et al, MRM 44:525-531, 2000.