SAR Reduction in Transmit SENSE Using Adapted Excitation k-Space Trajectories

X. Wu[1], C. Akgun[1], J. T. Vaughan[1], K. Ugurbil[1], and P-F. Van de Moortele[1]

[1]Center for Magnetic Resonance Research, University of Minnesota, Minneapolis, Minnesota, United States

Introduction: Severe transmit B_1 inhomogeneity occurs at very high field (1,2). Transmit SENSE (3,4,5) has been suggested as a potential method to address this issue by acceleration of multidimensional selective excitation. However, the specific absorption rate (SAR) is a main concern, especially at high field, that might limit further applications of Transmit SENSE. Indeed, previous studies (6,7) showed that SAR increases with the reduction factor. In this work, we propose for the first time a novel way to significantly reduce SAR in Transmit SENSE using adapted-rate excitation k-space trajectories while preserving most of temporal acceleration. This new technique was verified with simulations for an 8-channel transmit coil array at 7T with a human head model.

Theory: Energy absorption depends quadratically on electric field, and hence SAR reduction can be achieved by flattening RF pulses. Based on the VERSE principle (8), the gradient can be adapted by $\vec{G}_{ad}(t) = \vec{G}(\tau(t))\dot{\tau}(t)$ and the adapted RF pulses for the same excitation pattern would be $b_{ad,n}(t) = b_n(\tau(t))\dot{\tau}(t)$. Here, $\vec{G}(\tau)$ and $b_n(\tau)$ are respectively the original gradient and RF pulses, and $\tau(t)$ is some function of time with $\tau(0) = 0$ and $\tau(T_{ad}) = T$. Hence, one can reduce SAR by finding a $\tau(t)$ such that $\dot{\tau}(t)$ is less than unit during peaks of RF pulses.

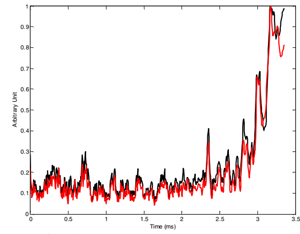

FIG. 1. SOM of pulses (black) and the spatial average of electric field magnitude (red) for the centered oval target.

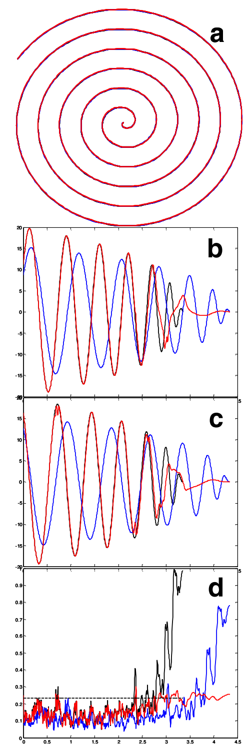

FIG. 2. a: trajectories. **b:** Gx. **c:** Gy. **d:** SOMs and the threshold (dashed line). (black: original; blue: stretched; red: adapted.)

Methods: The coil used in the model is an 8-element RF stripline coil array (9) mounted on a cylindrical former of 32cm in diameter and loaded with a human head. Transmit B_1 and electric field maps in the brain were simulated with the XFDTD software (REMCOM Inc.). Given a target, 2D-selective RF pulses were first calculated with a slew rate-limited (160T/m/s) spiral gradient (3.4ms) designed for a reduction factor of 4 using Glover's algorithm (10). In order to efficiently reduce SAR, the electric field would be the ideal reference to modulate the gradient. However, electric field maps cannot be measured experimentally and hence we used the sum of magnitudes (SOM) of the 8 RF pulses which we found strongly correlated to the net electric field as shown in Fig. 1. Starting with the fastest possible spiral gradient, an adapted rate was obtained by decreasing the rate of traversal in k-space whenever SOM was above a threshold defined as the temporal average of SOM. Additionally, the modified gradient waveforms were smoothed in order to never exceed the maximum slew rate. To show the advantage of this technique, we compared the SAR of the pulses calculated with adapted gradient to that of those pulses with stretched gradient of the same duration but here generated by uniformly slowing down the original traversal. Three different targets (see Fig. 3a) were used for designing pulses, and the field of excitation (FOX) was defined on a 48x48 matrix with a 4.4-mm resolution. Pulses were calculated with simulated transmit B_1 maps using the spatial domain method including ROI mask (11) and the conjugate gradient algorithm was employed to solve the inverse problem. Finally, SAR behavior within an axial slice of the brain was obtained based on the electric field maps from the simulation. All calculations were performed in MATLAB (The MathWorks Inc.).

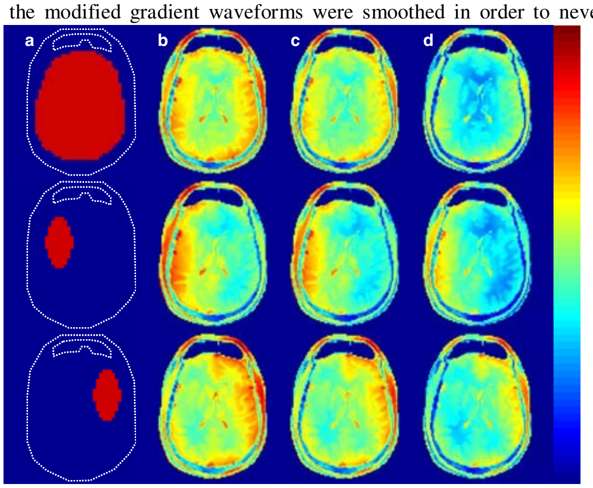

FIG. 3. Spatial distributions of the absorbed energy for different excitation targets when pulsing with different gradients. **a:** target and ROI mask (dashed shape); **b,c,d:** absorbed energy for original, stretched and adapted gradients, respectively. (All maps are in arbitrary unit. For each target, maps are scaled to the range [0 1] and displayed with a logarithmic color scale.)

Results and Discussion: Fig. 2 shows the original (black), stretched (blue) and adapted (red) gradients and the corresponding SOMs for the centered oval excitation pattern. One can see that when a peak in the original SOM is above the threshold, the adapted gradient decreases and elongates correspondingly, which in turn makes the adapted pulses longer than the original pulses but much flatter than both the original and stretched ones. Fig. 3 shows the spatial distributions of the absorbed energy in the axial slice during the pulse when using Transmit SENSE for different targets with different gradients. The maps indicate that for all targets the overall absorbed energy of the adapted pulses is the least, and that of the original pulses is the greatest. The numerical values displayed in Tab. 1 indicate that the total absorbed energy using the adapted pulses can be reduced by 46~59% at the cost of a 26% longer duration as compared to using the original pulses. It should be noted that the average power during the adapted pulse would be more reduced than the absorbed energy since the pulse duration increases. Moreover, with the same length, the adapted pulses only induce 53~68% of the absorbed energy caused by the stretched ones, indicating that adaptively reducing the rate of traversal is significantly more efficient for SAR reduction than uniformly reducing the rate. In good agreement with Ref.(5), our data also show that both spatial distribution and numerical values of the absorbed energy depend on the excitation target, and we observe hot areas mostly in the periphery.

Target	centered oval			ellipse on the left			ellipse on the right		
Trajectory	original	stretched	adapted	original	stretched	adapted	original	stretched	adapted
Pulse duration (ms)	3.4	4.3		3.4	4.2		3.4	4.2	
Absorbed energy (a.u.)	13.91	10.75	5.75	3.93	3.11	2.10	3.88	3.08	2.10
Absorbed power (a.u.)	4.09	2.50	1.34	1.16	0.74	0.50	1.14	0.73	0.50

TAB. 1. Absorbed energy and average power for different excitation targets and gradients.

Conclusion: The results of this work show that the absorbed energy, as well as average power, during a Transmit SENSE pulse can be significantly reduced using adapted-rate excitation k-space trajectories. With a reduction factor of 4, our adapted RF pulses allowed for a SAR reduction of 46~59% with only 26% longer pulse duration as compared to the fastest pulses.

References: **1.** H. Bomsdorf, et al., NMR Biomed 1988, 1(3):151-158. **2.** J. T. Vaughan, et al., MRM 2001, 46(1):24-30. **3.** U. Katscher, et al., MRM 2003, 49:144-150. **4.** Y. Zhu, MRM 2004, 51:775-784. **5.** P. Ullmann, et al., MRM 2005, 54:994-1001. **6.** U. Katscher, et al., Proc. ISMRM 2005, p.17. **7.** P. Ullmann, et al., Proc. ISMRM 2006, p.601. **8.** S. Conolly, et al., JMR 1988, 78:440-458. **9.** G. Adriany, et al., MRM 2005, 53(2):434-445. **10.** G. Glover, MRM 1999, 42:412-415. **11.** W. Grissom, et al., MRM 2006, 56:620-629. **Acknowledgments:** This work was supported by BTRR - P41 RR008079, KECK Foundation.