Reduced-Voltage RF Shimming for Adiabatic Pulse Design in Parallel Transmission

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Introduction: Adiabatic pulses play an important role in magnetization inversion in the presence of B1 field inhomogeneity. In this work we propose the use of an adiabatic slice selective inversion pulse for parallel RF excitation design. A novel RF shimming algorithm is used to reduce the peak voltage required for the inversion. While the B1 shimming algorithm can be applied in principle to any adiabatic pulse, it is demonstrated here with a hyperbolic secant pulse [1]. Simulation results show that significant reductions in peak voltage and slice inversion non-uniformity can be achieved when compared with traditional RF shimming methods.

Methods: RF shimming for Adiabatic Inversion: Conventional RF shimming methods aim to make both the amplitude and phase of the B1 field spatially uniform across the excitation area [2]. This is achieved by applying different amplitude and phase to the RF pulses of each excitation coils. Mathematically, this problem can be stated as: $\min_b \sum_{x,y} \left\| B_1(b,x,y) - B_{1MEAN}(b) \right\|_2$, where b is the complex vector of voltages applied to the coils, $B_1(b,x,y)$ is the resultant B1 field after shimming, and B_{1MEAN} is the average field across the profile. To achieve uniformity, cancellation of the B1 fields produced by the excitation coils is needed; suggesting increased RF amplitudes are required. Using an adiabatic RF pulse to create uniform inversion places no restriction on the uniformity of the amplitude and phase of the B1 field. It is only required that the B1 field across the volume be above a certain threshold. It can be seen that the conventional RF shimming is more restrictive than what is required for adiabatic inversion. To reduce SAR, it is desirable to achieve the inversion at the lowest voltage which satisfies the adiabaticity conditions. With this in mind, we propose the following optimization algorithm to calculate the complex ratio of the voltages used in RF shimming of adiabatic pulses: $\max_b \left\{ \min_{x,y} \left| B_1(b,x,y) \right| \right\}$ such that $|b| \le 1$. We seek to maximize the minimum B1 field for the case where all the voltages applied to the coils are restricted to be less than a cutoff amplitude (normalized to one here). Once this optimization has been carried out, to perform the inversion, the resulting voltages are scaled up so that the minimum B1 field after shimming is above the threshold required for adiabaticity. **Bloch Simulation:** Performance of the traditional and the new algorithms for RF shimming are compared in the case of adiabatic inversion using an 8-channel loop coil array used previously for parallel excitation [2]. The well-known hyperbolic secant slice selective inversion pulse is used, with slice thickness of 0.5 cm, TBW of 10, and pulse duration of 9 ms.

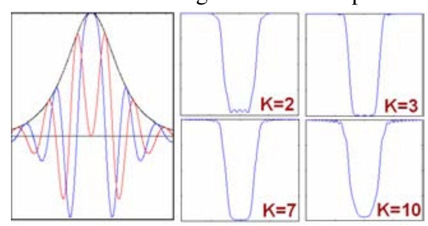

Fig1. Hyperbolic secant pulse (left), and the resulting slice selective inversion at various adiabatic factors (right)

Results and discussion: Fig1. shows the simulated result of the adiabatic inversion at various B1 field amplitudes, and values of corresponding adiabatic factor (k). It can be seen that the hyperbolic secant pulse creates a uniform slice selective inversion when the B1 amplitude is above a certain threshold (around k = 3), and is relatively insensitive to increases in RF amplitude over this threshold performing well up to around k = 8. Fig2. shows the B1 field distribution after the RF shimming algorithms have been applied. The 8–channel coil array used for parallel excitation is not particularly suited for RF shimming. Large central dips can be observed (top row) when the traditional shimming is used. Also shown (center row) is a relaxed traditional shimming where the uniformity has been traded off for reduced voltage by cutting off low eigenvalues in an SVD-based inversion. Shown in the bottom row is the resulting profile when the new shimming algorithm is used. Although the phase is less uniform, this is unimportant for the adiabatic pulse. On the other hand, the resulting B1 magnitude is much more uniform (B1max/B1min ratio are 3.5, 3.3, and 2.1 for the three methods). This is because, in the traditional shimming algorithm, one seeks to satisfy the magnitude and phase uniformity simultaneously. This results in widespread B1 cancellation between the coils and the resulting dip in the middle of the profile. For the new algorithm, the minimum B1 field is maximized, so the B1 field from the coils will try to add coherently, resulting in the enhanced magnitude uniformity, and more importantly, allowing the adiabatic condition to be maintained with lower average power. The ratio of the minimum B1 magnitude across the profile to the given maximum allowable voltage on the coils is 0.36, 0.48, and 1.00 for the three methods. Therefore, the B1 can be scaled down by this factor and still maintain the adiabatic condition providing a peak power reduction factor of ~7.7 $(1/0.36)^2$ over traditional shimming and ~ 4.3 $(1/0.48)^2$ over relaxed shimming method. The inversion profiles for the adiabatic pulse design using the various shimming methods are shown in Fig3. The voltages used for the coils are scaled such that the minimum B1 field has an adiabatic factor (k) of 3. The resulting inversion profile at z = 0 and 0.15 cm are shown on the left of Fig.3 (a&b). Large ratio of B1max/B1min in the traditional and the relaxed traditional methods cause the adiabatic factor (k) in region of high B1 field to be very high (>8), causing suboptimal slice selection in this region as seen in Fig 3 (b1&b2 at z = 0.15 cm). On the other hand, this ratio is small in the new shim method, resulting in very uniform profile. We also note that the peak voltage reduction is dramatic, from 730V to 260V for the proposed vs. traditional RF shimming. **Conclusion:** A novel RF shimming algorithm has been proposed and evaluated for an 8-channel loop array for the design of adiabatic inversion for parallel excitation. Simulation results show a significant reduction in peak voltage and improved slice inversion uniformity when compared with traditional RF shimming methods.

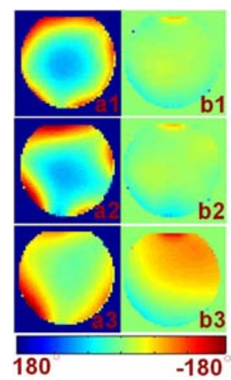

Fig2. Magnitude (left) and phase (right) after traditional RF shimming (top), relaxed traditional shimming (center), and new shimming (bottom).

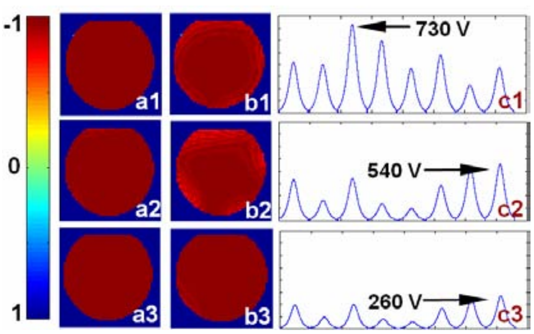

Fig3. Inversion profile at z = 0 (left), z = 0.15 cm (center), and the concatenated magnitude of the adiabatic pulse used on the 8 coils (right); for traditional shimming (top row), relaxed traditional shimming (center row), and new shimming (bottom row)

Acknowledgements: Siemens Medical Solutions, NIH P41RR14075, R. J. Shillman Career Development Award.

References: 1. Silver M.S., Joseph R.I., Hoult D.I., JMR 1984:59:347 **2.** Setsompop K. et al, MRM 2006:56:1163.