SAR Reduction using Non-Linear Gradients

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Introduction: In conventional MRI, linear gradients are used for slice selection as well as frequency and phase encoding purposes. Although non-linear gradients were previously used for frequency and phase encoding [1], recent studies still aim at removing the non-linearity in the field for slice selection [2].

Due to the Fourier Transform relation between the slice profile and the time waveform of the excitation RF pulse [3], apodized *sinc(t)* type pulses (Fig. 1) are widely used so that the slice profile is close to a rectangular function. However, *sinc(t)* pulses are far from being optimum, when SAR is considered. SAR is proportional to the integral of the square of the RF envelope whereas flip angle α is proportional to the integral of the envelope. Note that, when RF envelopes are compared in terms of SAR, flip angles should be the same, for consistency. In terms of SAR, a rectangular pulse is ideal (Fig. 1). However, slice profile for a rectangular pulse is a *sinc* function, which is not desirable. It was shown that a rectangular-pulse can be approached by varying the gradient signal in time [4], but the method is limited by the slew rate and maximum gradient waveform constraints. In addition, the off-resonance behavior for this design is not optimum [5] and the resulting RF waveform still has negative peaks, which increases the required SAR to achieve a given flip angle.

In this study, a novel method that employs non-linear gradient fields with constant gradient waveforms is proposed. The method enables slice selection with a rectangular-pulse and hence reduces SAR significantly.

Theory: Using the small tip angle formulations given in [3], the transverse component of the magnetizations (slice profile) inside a sample can be obtained as $m(z) \propto S(f')$ where $f' = \bar{\gamma}\,\Delta B(z)$, $\bar{\gamma}$ is the gyromagnetic ratio, $S(f)$ is the Fourier transform of the RF envelope and $\Delta B(z)$ is the gradient field. When the gradient field is linear, the slice profile is just a scaled version of the frequency spectrum. However, for a non-linear gradient field, different parts of the frequency spectrum observe different effects (Fig. 3). A portion of the spectrum that observes a slowly changing field gets widened (dark gray shaded region, Fig. 3) whereas a fast changing field leads to contraction (light gray shaded regions, Fig. 3). This technique can be used to modify the frequency spectrum of a rectangular pulse into a feasible slice profile.

In MRI, it is desirable to have an RF envelope that has *i*) low SAR, *ii*) high flip angle, *iii*) a uniform slice profile and *iv*) a high ratio of signal from inside the region of interest (ROI) to signal from outside of the ROI. By normalizing SAR with the square of the flip angle, two pulses can be compared in terms of SAR for a certain flip angle. A second figure of merit is slice selection performance, which is defined by subtracting the signal received from outside of the ROI from the signal from inside of the ROI and expressing the ratio of the resulting signal level to the available signal inside the ROI as a percentage.

Materials and Methods: To verify the theory, simulations are made using MATLAB (Mathworks, Natick, MA) and experiments are conducted on a Siemens TimTrio 3T system. An original FLASH sequence is obtained from Siemens for research purposes. The original sequence and a modified version with a rectangular RF waveform are used for the experiments. Both sequences have TE=4.8ms and TR=9.1ms and the slice thickness is 5.2 cm.

For realistic designs, the non-linear gradient field has to be terminated at a certain distance. For initial experiments, we designed a gradient coil (Coil: Fig. 2, Field: Fig. 3) using the target-field-method [6]. When used together with the linear z-gradient of the scanner, the field produced is as seen in Fig. 3. For determining the slice profiles experimentally, the x-gradient amplifier of the scanner is turned off, and its signal is used to feed the custom-made coil through a separate amplifier. During slice selection, the custom coil and the linear z-gradient are active, whereas only the z-gradient is active during readout. Phase encoding is along y. The measured slice profiles from MR images are normalized with the flip angle values at the center and are shown in Fig. 4 for both methods. Using phase data, the negative peaks in the slice profile of the proposed method are corrected. Slice profiles of both methods are calculated as follows. The RF waveforms are recorded using an oscilloscope and Fourier transforms of the envelopes (Fig. 1) are obtained with MATLAB. Finally, the non-linear gradient field of the custom made coil is measured, and then linear and non-linear gradient functions are applied to the frequency spectrums of the envelopes using $m(z) \propto S(f')$, respectively. The slice profiles are shown in Fig. 4. The calculated slice profiles and the ones obtained using MR images are in agreement (Fig. 4). It can be seen that the slice profile of the proposed method is considerably sharper than that of the FLASH sequence.

The proposed method yields 41% less SAR for the same flip angle level (envelopes: Fig 1). Outside the ROI, the slice profile of the proposed method alters signs, which provides signal cancellation. The slice selection performance of the proposed method is 94% whereas it is 71% for the conventional method. Note that the RF envelope of an original FLASH sequence has no side lobes. For a *sinc(t)* envelope with one or more side lobes, the slice selection performance will increase, however SAR per flip angle square will also increase, hence the reduction in SAR may be higher than 41%.

Conclusion: A novel method that employs non-linear gradients to perform slice selection with a rectangular pulse is proposed. The method yields significant reduction in SAR (41% is shown) while achieving the same flip angle. Furthermore, the proposed method increases the slice selection performance.

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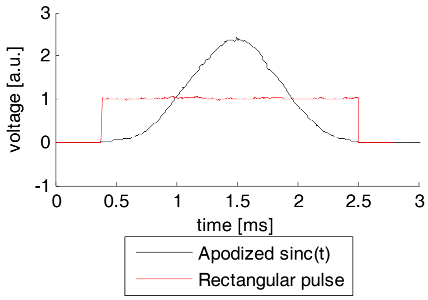

Fig 1: RF envelopes (baseband) that yield the same flip angle for an apodized *sinc(t)* (FLASH) and a rectangular pulse (proposed method).

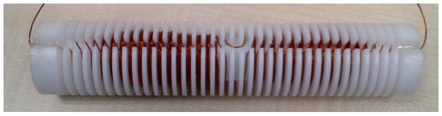

Fig 2: Custom-made gradient coil. Length: 20cm, inner diameter: 2cm.

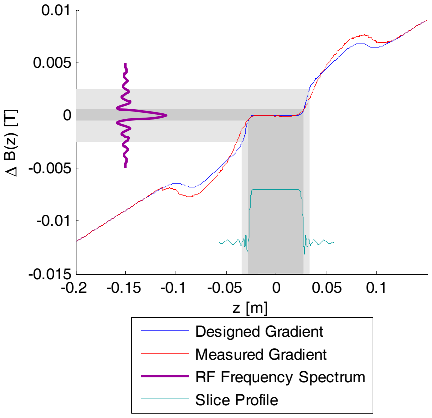

Fig 3: The designed and measured gradient field of the custom coil. The expansions and contractions in the slice profile are indicated by the gray shaded regions.

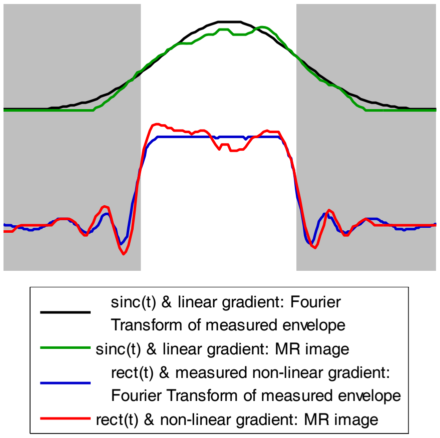

Fig 4: Slice profiles (vertical axes) for both the conventional and the proposed method. White background: inside of ROI, width: 5.2cm. Gray background: outside of ROI. Profiles for *sinc(t)* are shifted for clarity.