Characterization and correction of eddy currents for ultra high field parallel transmission with RF pulse design

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Introduction: Hardware and experimental imperfections can severely impact the performance of parallel transmission. Several techniques, such as shielded gradients [1], pre-emphasis system [2], and k-space trajectory measurement [3] have been demonstrated to compensate the eddy currents on gradient coil, but either they are not effective to compensate the gradient coil induced eddy currents in the RF shield or the correction is too time-consuming and inaccurate. In this work, we propose a new eddy current correction method combining existing eddy current characterization method [5, 6] for parallel transmission RF pulse design to compensate the overall distortion induced by gradient and RF coils as well as the system delay to reduce the distortions in parallel transmission.

Method: (Eddy Currents Characterization) Eddy current magnetic field are typically characterized as B_0 eddy current and linear eddy current, which represent the first and second terms of Taylor expansion. According to the simple eddy current model [5, 6], the magnetic field of eddy currents $G_E(t)$ induced by the gradient waveform $G_D(t)$ can be approximately formulated as the convolution of the eddy current impulse response function H(t) and the negative time derivative $-dG_D(t)/dt$ of the ideal gradient waveform $G_D(t)$.

$$G_E(t) = -\frac{dG_D(t)}{dt} \otimes H(t) \quad (1) \qquad H(t) = u(t)\sum_{n=0}^{N-1} \alpha_n e^{-t/\tau_n} \quad (2)$$

where the eddy current impulse response function H(t) can be modeled as the sum of multiple exponential terms that are characterized by amplitude α_n and time constant τ_n as in Eq. 2. The sign $\otimes$ denotes the convolution and u (t) is the unit step function.

The method proposed by Atkinson et al [7] is employed to completely characterize the system delay, B_0 and linear eddy currents. The problem of solving system constant, including system delay and eddy current coefficients (amplitude and time constant), can be formulated as the constrained minimization problem. Data are acquired by applying calibration gradient waveforms multiple times at different amplitudes and slice locations. Finally, the full set of system constants can be obtained by using iterative nonlinear fitting method to solve the aforementioned minimization problem for each physical gradient.

(RF pulse design) The effect of eddy currents combined with the small tip angle RF pulse design [8] is used to generate the pulses for parallel transmission. The RF pulses are solved from the following equation via magnitude least square optimization [9],

$$\mathbf{b}(t) = \arg\min_{\mathbf{b}}\{\| \, |\mathbf{Ab}| - \mathbf{m} \, \|_{\mathbf{w}}^2 + \lambda \| \mathbf{b} \|^2\} \quad (3)$$

All human brain studies were performed on 7T Siemens (Erlangen, Germany) scanner equipped with PTX extension. An 8-channel Tx/Rx coil was used and the RF waveforms for each Tx channel can be driven with independent waveforms. The RF design was implemented in Matlab R2009a (Mathworks, Natick, MA, USA). The desired excitation pattern was a smoothed rectangle with FOV of 220mm×220mm. A spiral-out trajectory was designed based on the method proposed by Glover (10) with maximum amplitude of 24 mT/m and maximum slew rate of 150 mT/m/ms. To investigate the proposed method, uncorrected and corrected RF pulses were designed using nominal gradient (G_D) and actual gradient (G_D+G_E), respectively for simulations and experiments.

Results and Discussion: Figure 1 shows a comparison of the nominal and actual gradients, corresponding k-space trajectory and sum of magnitudes of the eight RF pulses based on nominal (uncorrected) and actual (corrected) gradients. Note that the deviation of the actual gradient waveform and k-space trajectory compared with their nominal counterparts, resulting in noticeable difference in the RF shape between uncorrected and corrected pulses. Figure 2 shows the comparison of excitation performance of uncorrected and corrected RF pulses over different acceleration factors (R=2, 4, 6) for simulations and experiments, respectively. The excitation patterns were obviously distorted by eddy current field and significantly improved by the proposed correction method. RF pulse durations for acceleration of 2, 4 and 6 were 6.65ms, 3.34ms and 2.24ms, respectively. Window/level was adjusted to help visualize comparisons. Note that good agreement was achieved between simulations and experiments. As the acceleration factor is increased, the distortion is more severe for both simulations and experiments due to highly undersampling k-space at high acceleration.

Conclusions: We have introduced an effective method for designing parallel transmit RF pulses to correct the eddy current field, and demonstrated its ability to improve the excitation accuracy. Our proposed compensation method is a straightforward and easy to implement, but yields an evident improvement in the performance of spatially localized excitation of parallel transmission.

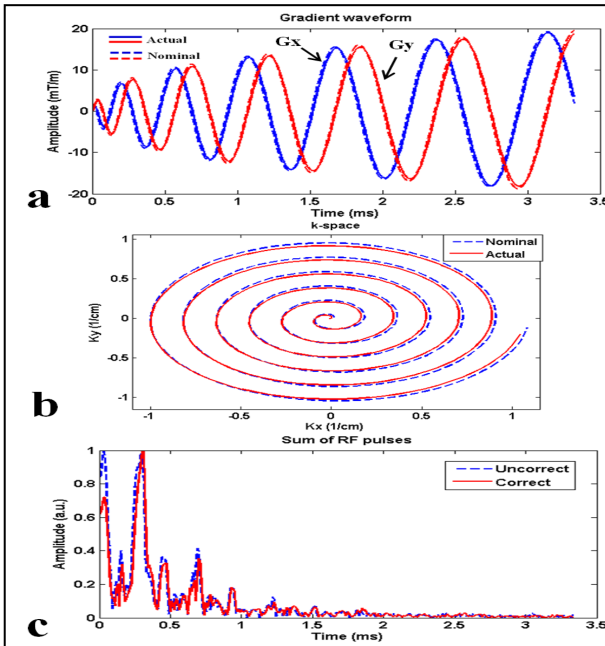

Fig.1 Comparison of nominal and actual (a) gradient waveforms, (b) k-space, (c) sum of RF pulses at R=4.

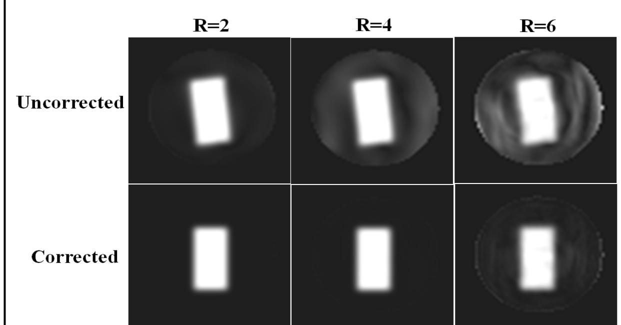

Fig.2 (Simulation) Comparison of uncorrected (top row) and corrected (bottom row) RF pulses excitation.

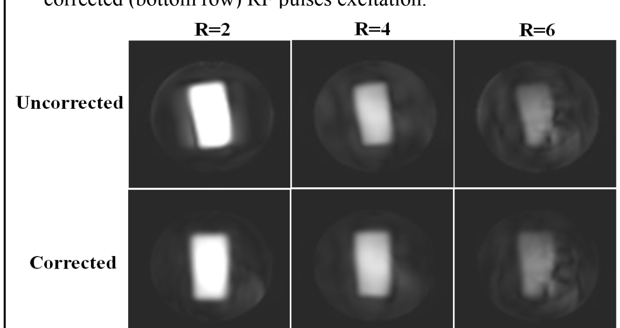

Fig.3 (Experiment) Comparison of uncorrected (top row) and corrected (bottom row) RF pulses excitation.

Reference: [1] P.Mansfield et al., J Phys E19:L129, 1986. [2]R.E.Wysong, et al., MRM 31:572-575 1994. [3] A. Takahashi et al., MRM 34:446-456, 1995. [4] I. Atkinson et al., MRM 62: 532-537, 2009. [5] Van Vaals et al, JMR 90:52-70, 1990. [6] P. Jehenson et al, JMR 90: 264-278, 1990. [7] Atkinson IC, et al., MRM 2009;62:532-537. [8] W Grissom et al.,MRM 56:620-629.2006. [9] Setsompop K, et al., MRM 2008;59:908-915. [10] Glover GH. MRM 1999;42:412-415.