Optimization of Composite Pulses Considering Pulse Duration, Excitation Uniformity and SAR

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INTRODUCTION: To address challenges of B_1 nonuniformity in high field MRI, researchers have developed a variety of transmit array pulsing methods to improve excitation uniformity and reduce specific absorption rate (SAR). Except for RF shimming (1), these methods are generally expected to require longer pulse durations than their simple single-pulse counterparts can achieve. Because shortening a pulse generally requires higher B_1 fields and thus higher SAR, this leads to a compromise between excitation homogeneity, SAR, and pulse duration. In this work, we present pulse duration dependent optimization of array-optimized composite pulses (ACP) (2-4) for simultaneous improvement in excitation uniformity and reduction of SAR as compared to conventional quadrature excitation and simple pulses.

METHOD: An 8 channel transmit array (MR Instruments Inc, Minneapolis, Minnesota), having an inner diameter (ID) of 246 mm, a length (L) of 214 mm, and loaded with a human head was simulated at 300 MHz (7T) (Fig. 1). A human head model having 47 different tissue types with a 5 mm resolution was used for optimization (5) to save calculation time, whereas a 2 mm resolution head model was used for the MR simulator. The electromagnetic field properties of each coil element, B_1^+, B_1^- and electric field intensity (E), were calculated with the FDTD method. A conventional quadrature driving method using the same transmit array and head model was simulated for reference. For the ACP, the current magnitudes and phases of each element in both component pulses were optimized to maximize the transverse magnetization (M_t) at the end of the second component pulse and simultaneously reduce maximum local (one-cell) SAR. During optimization, a simple cost function (3), η×inhomogeneity + (1-η)×SAR, $0 \leq \eta \leq 1$, was minimized. M_t was evaluated within the 3D whole brain, and the whole head was used for SAR evaluations. All FDTD calculations were performed using commercially available software (xFDTD; Remcom, Inc; State College, PA) and optimization was performed using home-built code in Matlab (The MathWorks, Inc., Natick, MA).

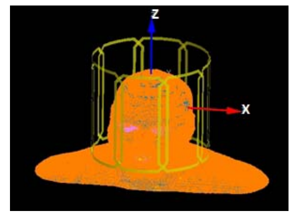

Figure 1 Geometry of transmit array and head model.

RESULTS: Fig. 2 shows the distribution of SAR and M_t for the transmit array with quadrature drive (first column), RF shimming (second column) and ACP (third and fourth column) throughout the region of interest (ROI), a 3D brain for M_t and a whole head for SAR. Fig. 3 shows the acquired proton density images with quadrature driving (left) and optimized composite (right). The pulse duration (3 msec) was minimized using VERSE technique (6). When η was increased from 0 to 1, the excitation uniformity was increased, whereas mean and maximum value of SAR was increased (Table 1). A good compromise was seen when η was 0.5 (Fig. 2 and Table 1) for the optimized composite. When η was 1.0 for the optimized composite with τ of 1.5 ms, compared to the quadrature drive (Table 1), the excitation nonuniformity was decreased about 79% whereas the mean SAR was increased about 211%.

DISCUSSION: With RF shimming, it is possible to greatly improve excitation uniformity over conventional quadrature drive (1). In cases where SAR is not a concern (η=1), an ACP (and a variety of other transmit array pulses) can achieve significantly better homogeneity than RF shimming alone at any pulse duration (2). If total pulse duration is not a concern, an ACP (and a variety of other pulses) can achieve both better homogeneity and lower SAR than RF shimming – but this may require unreasonably long pulse durations in some cases. If the total duration of the ACP is restricted to that of the single pulse, it can achieve better excitation homogeneity than a quadrature drive or RF shimming, but not both better homogeneity and lower SAR (1-4, Table 1). Depending on the frequency of interest, if the ACP is permitted to have a duration even slightly longer than that of the single pulse, it can again achieve better excitation homogeneity and lower SAR than a single pulse with a quadrature drive, but as the pulse duration is restricted the advantages of the ACP over RF shimming in cases where SAR is a limiting factor are reduced.

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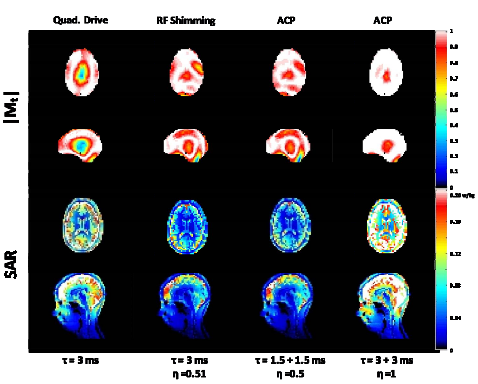

Figure 2 Numerical calculation results of SAR and M_t throughout selected slices of a head at 300MHz (7T) for quadrature driving (first column), and transmit array with RF shimming and ACP. τ is the pulse excitation time.

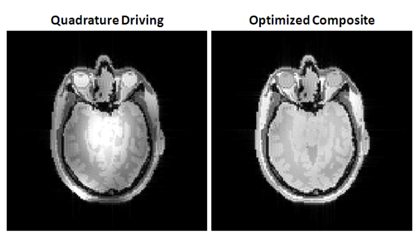

Figure 3 Proton density images of quadrature drive (left) and optimized composite pulse (right) when η was 0.5 in a freely available 3D MRI simulator (7).

Table 1 Numerical calculation results of excitation nonuniformity (second column), mean (third column) and maximum local (one-cell) SAR (fourth column). SAR values are for a TR of 200ms. Average Imperfection[2] of the excitation distribution is calculated as $[\Sigma(1-M_t)^2]/N$

	Inhomogeneity $\sum(1-M_{xy})^2 \div N$ $[10^{-3}]$	Mean SAR [mW/kg]	Maximum Local SAR [mW/kg]
Quadrature Driving (τ = 3 ms)	94.42	78.88	787.30
RF Shimmed (τ = 3 ms, η = 0.51)	90.55	42.53	389.22
RF Shimmed (τ = 3 ms, η = 1.0)	75.62	63.22	670.75
Quadrature Composite (Before Opt., τ = 1.5 + 1.5 ms)	39.79	315.50	3149.20
Optimized Composite (τ = 3 + 3 ms, η = 0.5)	88.60	21.53	224.21
Optimized Composite (τ = 3 + 3 ms, η = 1.0)	19.44	122.57	1177.70
Optimized Composite (τ = 1.5 + 1.5 ms, η = 0.5)	88.60	43.07	448.41
Optimized Composite (τ = 1.5 + 1.5 ms, η = 1.0)	19.44	245.14	2355.30