Large tip-angle, motion robust pulse design for parallel transmission at 7T using composite B1 distributions.

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Synopsis

Parallel-transmit (pTx) pulses can help overcome B1 inhomogeneity at ultra-high field, however their performance is sensitive to geometry, orientation and composition of the coil load. Head motion in pTx effectively alters the load, damaging pulse performance and reintroducing artificial contrast to images. Here, we introduce a versatile method to reduce in-plane motion sensitivity of large tip-angle, parallel transmit pulses by designing pulses based on weighted-average B1-distributions. These include B1-distributions from multiple head positions to effectively expand the area over which the pulse can function. Error in resulting inversion profiles is reliably reduced following most in-plane translations and rotations, demonstrating motion-robustness.

Introduction

Parallel transmit (pTx) arrays with tailored pulses (designed using the load-dependent B1-distribution) can help overcome characteristic B1-inhomogeneity at ultra-high field (UHF; ≥7 Tesla) MRI to produce uniform flip-angle throughout the imaged volume[1-4]. B1-mapping is usually conducted once and resulting pulses are used throughout the scan, effectively tailoring the pulse to the subject and their head position during the mapping.

It was previously shown that head motion commonly causes flip-angle error (normalised root mean-squared error; nRMSE) of 20-30% and up to 90% for large movements in the small tip-angle (STA) regime[5]. Our initial investigations indicate that the iterative nature of most large tip-angle (LTA) design methods augments motion-induced error and makes it less spatially uniform (data not shown).

Here, we generate composite B1-maps that cover a larger area than the head by weighted-averaging B1-maps that belong to multiple head positions. These averaged B1-maps are used to design LTA inversion pulses, which achieve an inversion profile in a larger area across the field of view, introducing motion robustness. Direction-specific pulses are designed offline, forming a library from which the pulse to play at any timepoint can be determined by head position.

Methods

B1-maps were generated using Sim4Life (ZMT, Zurich, Switzerland) with an 8-channel loop array tuned to 300MHz and the Ella body model (IT'IS, Zurich, Switzerland)[6]. In-slice head motion (1/2/5/10/15/20mm towards right, and/or 1/2/5/10mm towards posterior; or ±1/±2/±5/±10/±15/±20^{o} rotation) was simulated by displacing the body model with respect to the array[5].

180° spiral trajectory inversion pulses were designed using a fast optimal control algorithm[7] with either the central (i.e. unmoved) head position (P0) B1-distribution alone (conventional method), or the averaged, direction-specific B1-distribution (proposed method [Fig.1a]). Averaged distributions were defined as:

$$B1_{avg}(c,r) = \frac{\sum_{i=1}^{Np(r)} B1(i,c,r)w_i}{\sum_{i=1}^{Np(r)} w_i}$$

where *Np(r)* is the number of simulated positions in a given direction with non-zero B1-values in pixel *r* (e.g. *Np(r)* ≤7 'rightward' positions along -X), *B1(c,r)* is the *c*'th channel's complex B1-sensitivity at pixel *r*, and w_i is a position-specific weighting factor used to prioritise performance with small movement over large, accounting for the higher likelihood of small movements by cooperative subjects. This resulted in 4 off-central (right, posterior, +yaw, -yaw) pulses (Fig.1c). For yaw, pulses were also designed for 5 additional axial slices (separated by 20mm) since motion susceptibility of pTx pulses has previously been reported to be slice-dependent[5]. Inversion profiles were evaluated using Bloch simulations for each pulse at all positions. nRMSE of the resulting profile was calculated with respect to target profile (Fig.1b).

Results

In all translation cases, inversion profile was improved using the proposed approach (Fig.2). nRMSE was reduced compared to the conventional (P0) pulse by an average of 7.7% (max = 13%) for rightward (Figs.2a & 4b), and 2.4% (max = 3.8%) for posterior movements, respectively (Figs.2b & 4b). Benefits were also seen for off-axis positions (which were not included in the B1-averaging) for 92% of cases by using the rightward pulse, or 83% of cases using the posterior pulse. Representative small and large off-axis movements are shown in Fig.5. The posterior pulse did not improve performance when the off-axis position included a large rightward component (red box in Fig.5).

For -yaw, 79% of cases were improved using the proposed method. Qualitatively, the inversion profile remained smoother under yaw conditions when the direction-specific pulse was used (Fig.3). For +yaw, 38% of cases were improved. Though the inversion profile was reliably improved in slices 3&4, for peripheral slice locations (slices 1,2,5,6), the +yaw pulse did not improve performance (Fig.4a). Yaw ≥ 10° cases were omitted from Fig.4 for clarity since, although error was reduced relative to the conventional pulse, it remained at 40-60%.

Discussion

In-vivo implementation requires real-time positional information; possible with simple, low-resolution motion-tracking. When in-plane motion occurs, the appropriate direction-specific pulse is played out. Universal Pulses[8] and SmartPulse[9] are library-based approaches to reduce inter-subject anatomical variability effects on pulse performance while avoiding lengthy online pulse design. The method proposed here is versatile and conceptually compatible with both approaches, introducing motion-robustness to the library of pulses.

The direction of the B1-field curve (counter-clockwise; the same as +yaw) may explain the lower improvement rate for +yaw, and is subject of ongoing investigations. Though error for yaw ≥ 10° was not reduced to acceptable levels, this is likely due in part to the weighting values assigned during the B1-averaging (performance for small shifts was prioritised). If large movement is expected (e.g. paediatric subjects), a pulse designed using weights which prioritise extreme positions can additionally be used.

Motion-induced local-SAR increases of 50-100% are not uncommon in the STA regime[5]. Fig.1c waveforms show that peak power in pulses designed using the proposed method is comparable to that of the conventional pulse, so global-SAR management based on RF power should not be significantly affected. Local-SAR behaviour of the developed pulses is subject of current work.

Conclusion

We have introduced a versatile method to reduce in-plane motion sensitivity of LTA pTx pulses by using composite B1-distributions. These include multiple head positions to effectively expand the area over which the pulse can function, resulting in superior inversion profiles following motion. The method helps overcome one of the remaining obstacles for pTx to be used widely.

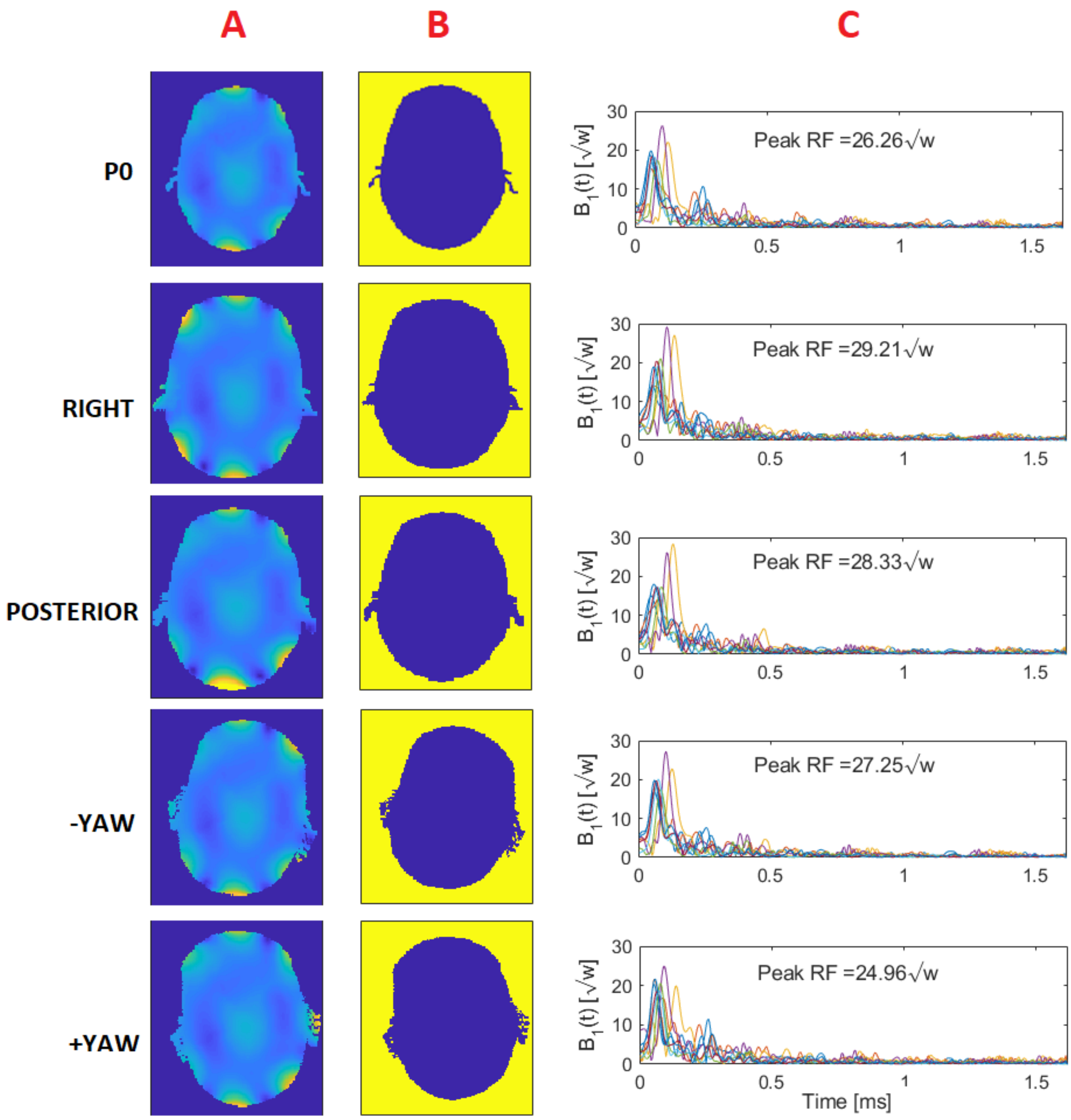

Figure 1. ***(A)*** *Averaged B1-maps used to design each direction-specific pulse (channel sensitivities displayed combined in quadrature mode). P0 represents the conventional approach using the B1-map derived from one central position. Note the larger areas (larger than the head) covered in the off-central, averaged maps.* ***(B)*** *Target inversion profiles specified for each pulse. Target* M_z *magnitude was -1 across the slice in all cases (i.e. 180°* *target flip-angle).* ***(C)*** *Spiral pTx RF waveforms and peak power for pulses designed using the corresponding B1-maps. Colours correspond to pTx channels.*

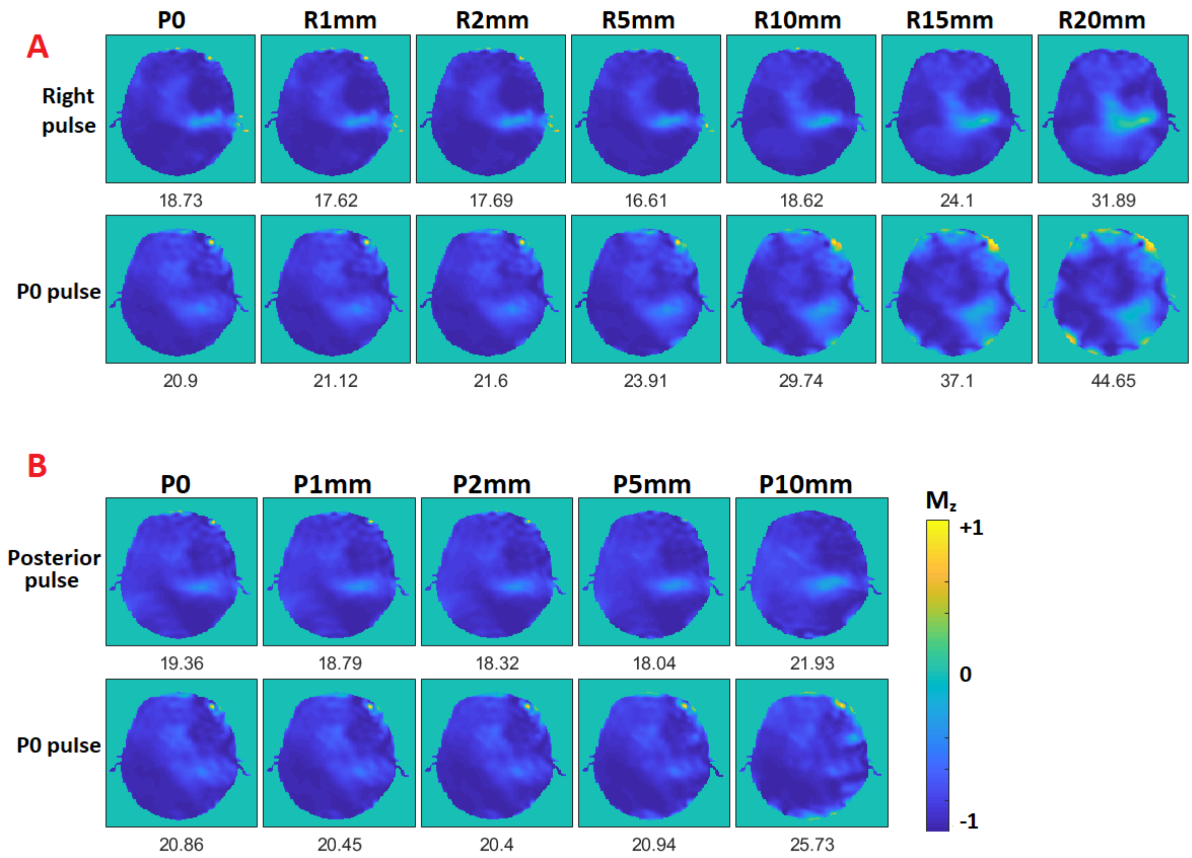

Figure 2. *Inversion profiles following in-slice translation for right **(A)** and posterior **(B)** movement. Positions are denoted by columns (i.e. R1mm = head shifted right by 1mm; P1mm = head shifted posterior by 1mm; P0 = central position). In both (right and posterior) cases, top row shows profiles obtained using the respective direction-specific pulse (proposed method) while the bottom row shows those obtained with the conventional (P0) pulse. nRMSE with respect to the target is reported below each profile. In all cases, error in the profile was reduced by using the proposed method.*

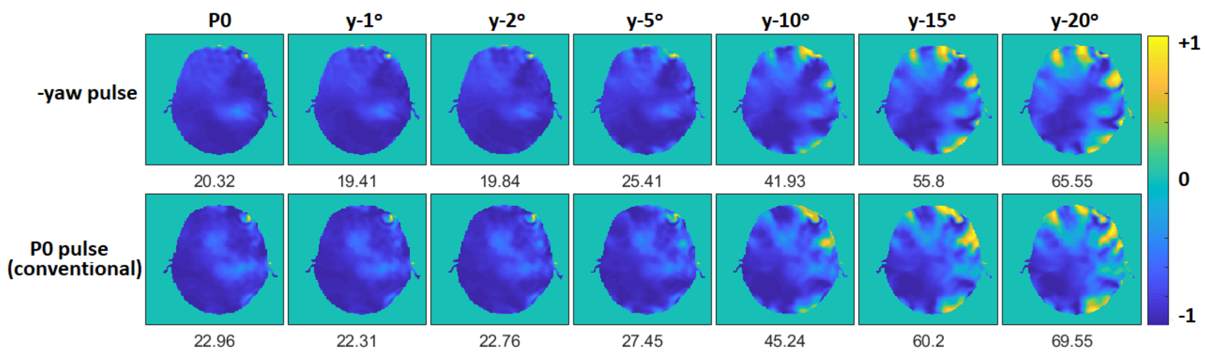

Figure 3. *Inversion profiles at slice 2 following in-plane rotation (-yaw). Top row shows profiles obtained using the direction-specific pulse (proposed approach); bottom row shows those with the P0 pulse (conventional approach). nRMSE with respect to the target is reported below each profile. In all cases shown, error in the profile was reduced by using the proposed method.*

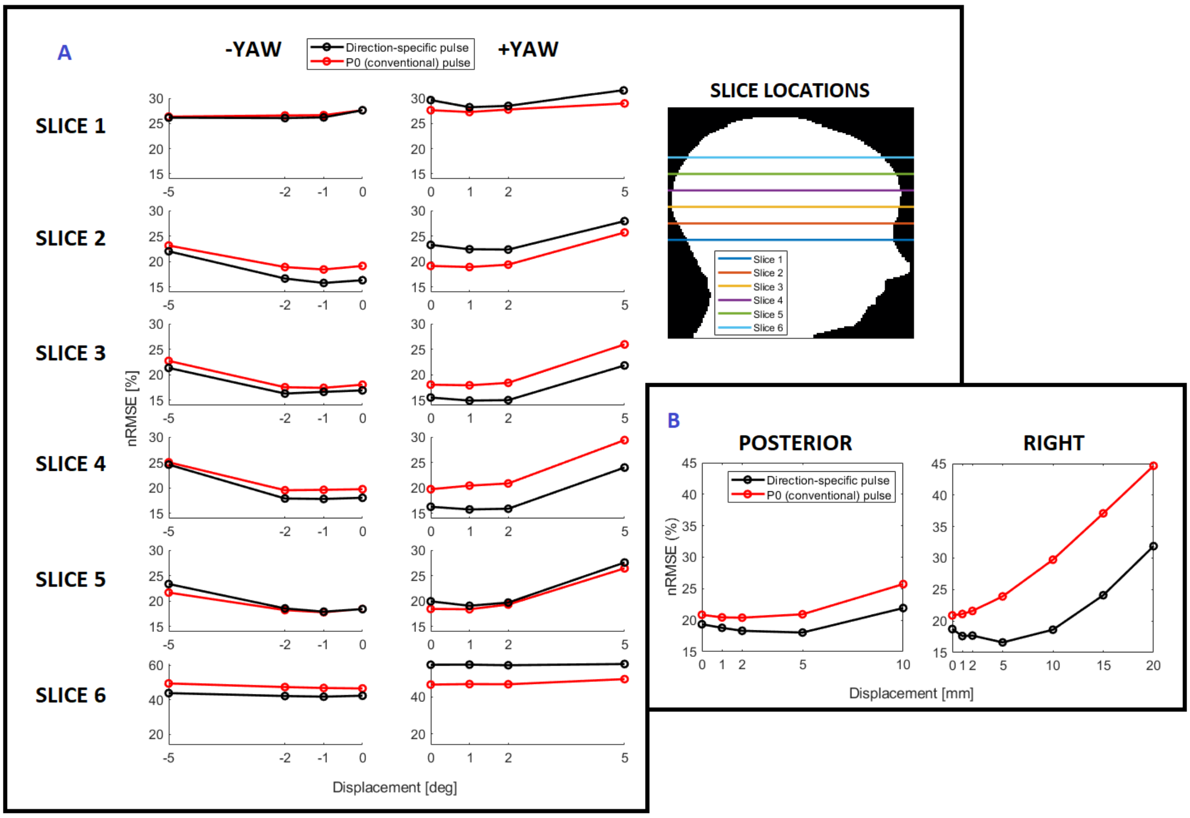

Figure 4. (A) *Error with respect to target profile for all slices tested with yaw. Slice number correspond to that shown in the slice location figure. Position is denoted on plots' x-axes. For -yaw, 79% of cases were improved using the proposed method, across all slice locations. For +yaw, the method reliably improved performance in slices 3 and 4, but not at outer slice locations. Large yaw motion (± ≥ 10°) is omitted from plots for clarity, but error was also reduced in these cases.* ***(B)*** *Error for posterior and rightward translations. The proposed method decreased nRMSE in all cases.*

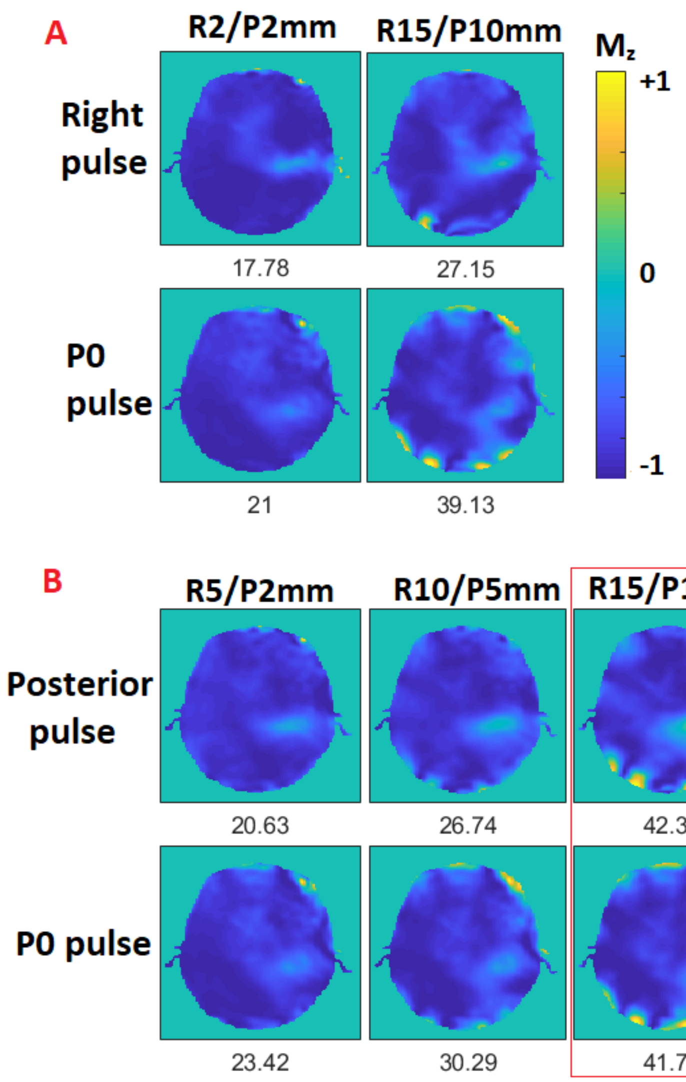

Figure 5. *Representative cases of large and small off-axis motion (combined rightward and posterior, denoted by columns [i.e. R2/P2mm = head shifted right by 2mm and posterior by 2mm]). These positions' B1-maps were not included in the B1-averaging process.* ***(A)*** *The rightward pulse reduced error in 92% of off-axis cases by an average of 8.4% (max = 13.2%) compared to the P0 pulse.* ***(B)*** *The posterior pulse reduced error in 83% of the same cases by an average of 2.6% (max = 3.8%). Red box indicates cases where the P0 pulse outperformed the posterior pulse.*

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