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TECHNICAL NOTE

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Interleaved binomial kT-Points for water-selective imaging at 7T

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Purpose: We present a time-efficient water-selective, parallel transmit RF excitation pulse design for ultra-high field applications.

Methods: The proposed pulse design method achieves flip angle homogenization at ultra-high fields by employing spatially nonselective k_T-points pulses. In order to introduce water-selection, the concept of binomial pulses is applied. Due to the composite nature of k_T-points, the pulse can be split into multiple binomial subpulse blocks shorter than half the precession period of fat, that are played out successively. Additional fat precession turns, that would otherwise impair the spectral response, can thus be avoided. Bloch simulations of the proposed interleaved binomial k_T-points pulses were carried out and compared in terms of duration, homogeneity, fat suppression and pulse energy. For validation, in vivo MP-RAGE and 3D-EPI data were acquired.

Results: Simulation results show that interleaved binomial k_T-points pulses achieve shorter total pulse durations, improved flip angle homogeneity and more robust fat suppression compared to available methods. Interleaved binomial k_T-points can be customized by changing the number of k_T-points, the subpulse duration and the order of the binomial pulse. Using shorter subpulses, the number of k_T-points can be increased and hence better homogeneity is achieved, while still maintaining short total pulse durations. Flip angle homogenization and fat suppression of interleaved binomial k_T-points pulses is demonstrated in vivo at 7T, confirming Bloch simulation results.

Conclusion: In this work, we present a time efficient and robust parallel transmission technique for nonselective water excitation with simultaneous flip angle homogenization at ultra-high field.

KEYWORDS

ultra-high field MRI, parallel transmission (pTx), k_T-points, water excitation

1 | INTRODUCTION

Increased static magnetic fields enhance the signal to noise ratio in MRI, allowing to acquire images with higher resolution or to reduce the acquisition time.[1] However, a problem emerging at ultra-high fields ($B_0 \geq$ 7T) are B_1^+ inhomogeneities due to radiofrequency (RF) interferences[2-4] and dielectric resonances.[5] Different solutions have been proposed to counteract the problems associated with B_1^+ inhomogeneities: Adiabatic pulses,[6,7] dielectric pads,[8] dedicated coil designs[9,10] and parallel transmission (pTx).[11,12] Parallel transmission has turned out to be particularly effective for subject specific and subject independent B_1^+ adjustments.[13-17] RF shimming solely sets fixed optimized amplitude and phase combinations on each transmitting channel to reach improved homogenization of the B_1^+ distribution.[18] pTx instead aims at a homogeneous flip angle distribution by transmitting different RF wave forms on each channel, while gradient pulses are applied to cover a certain transmit k-space trajectory.[19] However, combining pTx with fat suppression poses additional challenges at ultra-high fields.

In sequences with a low phase encoding bandwidth such as echo planar imaging (EPI) signal from fat appears displaced along the phase encoding direction. As a result of the chemical shift, severe image artifacts occur in the brain demanding for elimination of fat signal. But standard fat suppression methods require long durations or produce high specific absorbtion rates (SAR), particularly at ultra-high fields.

A single rectangular RF-pulse with a specific duration (RECT pulses)[20] offers a low-SAR, time efficient solution to eliminate fat signal. In the small tip angle approximation, the spectral response of a rectangular pulse is given by a sinc function and water excitation can be achieved by adjusting the roots of the sinc function to the resonance frequency of fat. A drawback of this method is the fixed duration of the pulse and the limitation to B_1^+ shimming, which in many instances does not provide sufficient degrees of freedom to homogenize the B_1^+-field across the entire brain.[18]

It has been proposed to combine RECT pulses with k_T-points,[21] which deposit energy at discrete points in transmit k-space, to use the full potential of pTx.[22] k_T-points consist of a limited number of rectangular excitation subpulses interleaved with gradient blips to travel between transmission points. The drawback of combining pTx homogenization and RECT pulses are increased pulse durations and therefore limited echo and/or repetition times of fast imaging sequences. At 7T each sub-pulse has to have a duration of approximately 1 ms, leading to a long total pulse duration. This method will be referred to as RECT k_T-points in this work.

Another method proposed by Malik et al. is water excitation using binomial pulses[23] with optimized binomial coefficients, where each RF-pulse is separately B_1^+-shimmed.[24] This method leads to shorter pulse durations, but no excitation k-space trajectory is involved.

Therefore, we propose interleaved binomial k_T-points pulses to achieve high image homogeneity and spectral selection while maintaining short RF-pulse durations. The basic approach is similar to the work described in Reference 24 but extended to pTx pulses, leveraging the full potential of multichannel transmission.

2 | METHODS

2.1 | Pulse design

All pulses were calculated and optimized in the small tip angle approximation using the Siemens pTx PulseDesign framework (Siemens Healthcare) implemented in Matlab R2012b (Mathworks). For all pulse calculations the standard B_0 and B_1^+ scanner calibration data was used.

Image homogenization was achieved by employing spatially nonselective k_T-points pulses,[21] and water-selection was introduced by applying the concept of binomial pulses.[23] In this work, k_T-points were located at the highest contributions of the inverse Fourier transform of the Bloch simulation of a RF-shimmed pulse, similarly to Reference 21, where the mask was taken into account. However, more elaborate methods can be applied to find k_T -point locations.

A straightforward approach, to create binomial pulses, is to repeat the k_T-points pulse when fat and water protons are out of phase, tipping the fat magnetization back to the longitudinal axis, see Figure 1B. In this case, the excitation k-space trajectory is the same as for a single pulse, but is repeated several times from beginning to end. However, if the total pulse length is longer than half the precession period of fat ($T_{fat}/2$), the second pulse has to be applied at an odd multiple of $T_{fat}/2$, leading to long pulse durations and significantly increased B_0 sensitivity as the spectral response is compressed accordingly. At 7T, $T_{fat}/2$ is only approximately 510 µs such that a spacing of $3T_{fat}/2$ or $5T_{fat}/2$ may be required to accommodate sufficient k_T-points subpulses. These will be referred to as standard binomial k_T-points pulses.

Due to the composite nature of k_T-points, the pulse can be split into sub-pulse blocks shorter than $T_{fat}/2$: The first subpulse block is repeated directly after $T_{fat}/2$, immediately followed by the second subpulse block played out in the same way, and so forth (Figure 1C). As a consequence, the excitation k-space trajectory is not traversed from beginning to the end in the same fashion as it would

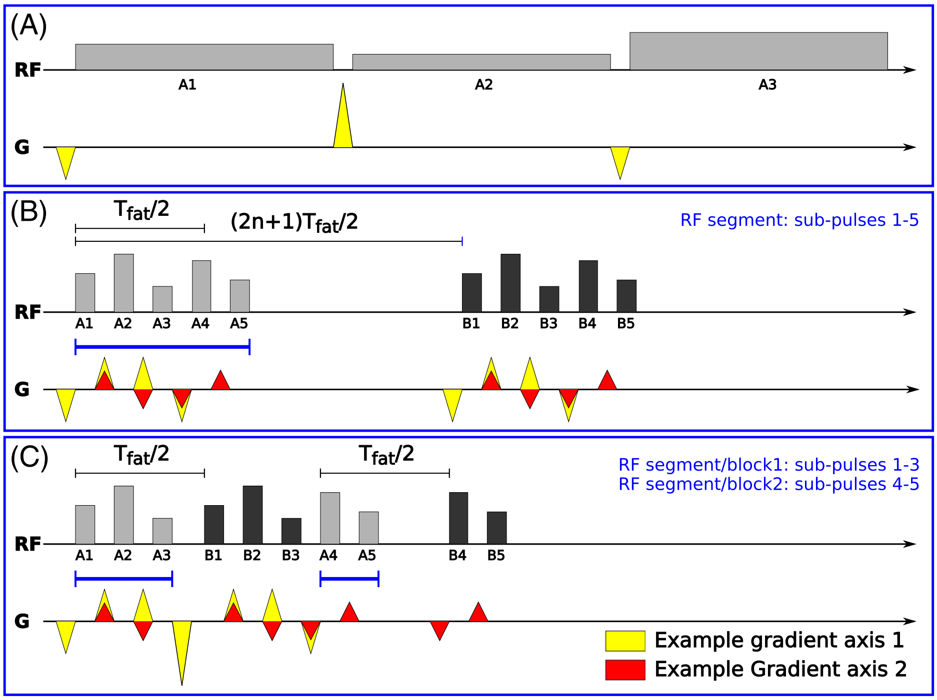

FIGURE 1 A comparison of different water excitation pulse schemes. (A) RECT 3 k_T-points water excitation (as used in Reference 22). (B) εStandardε binomial 1-1 excitation applied to a 5 k_T-points pulse. The pulse is repeated at an odd multiple of $T_{\text{fat}}/2$. (C) Proposed interleaved version of the binomial 1-1 5 k_T-points pulse. The pulse is split in two subpulse blocks, each shorter than $T_{\text{fat}}/2$. A1-5 and B1-5 denote the five subpulses of the two binomial k_T-points pulses. The blue bars indicate coherent radiofrequency segments.

be in a single non-water-selective pulse. Instead, the first point in k-space is visited again after a few subpulses, to apply the second RF pulse at this position precisely after $T_{\text{fat}}/2$. Using this method, B_0 sensitivity is not increased, as the first root of the spectral response of the binomial pulse is always at the resonance frequency of fat. This proposed method will be referred to as interleaved binomial k_T-points.

A python implementation of the proposed method can be found at https://github.com/mrphysics-bonn/interleaved_binomial_kTpoints.

For comparison, the RECT k_T-points method was implemented.[20,22] Each subpulse duration was adjusted to minimize the excitation of fat (~1 ms at 7T), see Figure 1A.

2.2 | Simulations

Pulse optimizations and Bloch simulations were performed based on B_0 and B_1^+ maps of a gel phantom without considering relaxation effects.

First, interleaved binomial k_T -points (Figure 1C) were compared to standard binomial k_T -points (Figure 1B) with regards to time efficiency. Both pulse types (standard and interleaved pulses) were simulated for different subpulse durations (10–180 μs) and for different binomial orders (1-1 and 1-2-1) at 7T ($T_{\text{fat}}/2 \sim 510$ μs). The resulting total pulse duration was compared for 5 and 7 k_T-points. A maximal subpulse duration of 180 μs was used, because longer subpulse durations would have resulted in blocks of one subpulse each.

Additionally, Bloch simulations of the interleaved binomial k_T-points pulse were carried out and compared to the RECT k_T-points pulse in terms of duration, homogeneity, fat suppression quality and pulse energy. In order to compare the fat suppression quality, the B_0 map was shifted to the fat frequency simulating a “fat-only” phantom. The influence of different numbers of k_T-points (5 and 7), different binomial orders (1-1 and 1-2-1) and different subpulse durations were investigated.

2.3 | Experiments

In addition to the Bloch simulations, the performance of different pulses was compared for a gel phantom and in vivo using an MP-RAGE sequence[25] as well as three-dimensional (3D)-EPI.[26] The MP-RAGE sequence utilizes a standard adiabatic inversion pulse in CP-mode (circular polarization) and both sequences use pTx excitation pulses for the gradient echo train.

For comparison of the homogenization quality, a CP-mode based 100 μs rectangular pulse, a RECT pulse with 3 k_T-points (1.02 ms subpulse durations) and two different interleaved binomial k_T-points pulses (5 k_T-points with 100 μs subpulses binomial 1-1 and 7 k_T-points 50 μs subpulses binomial 1-1 pulses) were used with a nominal flip angle of 8° in the gradient echo train of the MP-RAGE sequence. Using these pulses and the corresponding B_0 and B_1^+ maps of the subject, Bloch simulations were performed to estimate the flip angle distribution in the brain.

Finally, the fat suppression quality was also compared in vivo using the 3D-EPI sequence with representative whole-brain fMRI settings. Excitation types included a RECT pulse with 3 k_T-points, two different interleaved binomial k_T-points pulses (5 k_T-points with 100 µs subpulses binomial 1-1 and 1-2-1 pulses) and a single CP-mode-based 100 µs rectangular pulse (no fat suppression).

The imaging parameters of the MP-RAGE sequence were: TI = 1100 ms, TE/TR: 5.1 / 2500 ms, turbofactor 176, 1mm^3 isotropic resolution, readout pixel bandwidth = 110 Hz. The sequence utilizes an optimized linear reordering scheme with elliptical scanning and two-dimensional parallel imaging (a $2 \times 2_{z1}$ CAIPIRINHA sampling with a CAIPI shift of 1 in secondary phase encode direction was used).[27,28] The total scan time was 2:23 min.

3D-EPI imaging parameters were: TE = 20 ms, TR = 2.2 s, 1.5 mm^3 isotropic resolution, readout pixel bandwidth = 1754 Hz, sagittal slice orientation, posteroanterior primary phase encoding direction. A $3 \times 2_{z1}$ blipped-CAIPI sampling was used.[29]

The pulse design was implemented on a MAGNETOM 7T Plus scanner (Siemens Healthcare) using a head array coil with 32 receive and eight transmit channels (Nova Medical). For the in vivo measurements, the pulse calculation was performed online during the actual imaging session. In vivo experiments were performed in accordance with guidelines set by the institutional review board and prior, written informed consent was obtained from the subjects.

3 | RESULTS

3.1 | Simulations

Figure 2 shows the total pulse duration for the standard and interleaved binomial k_T-points pulses, plotted against the total duration of the corresponding,

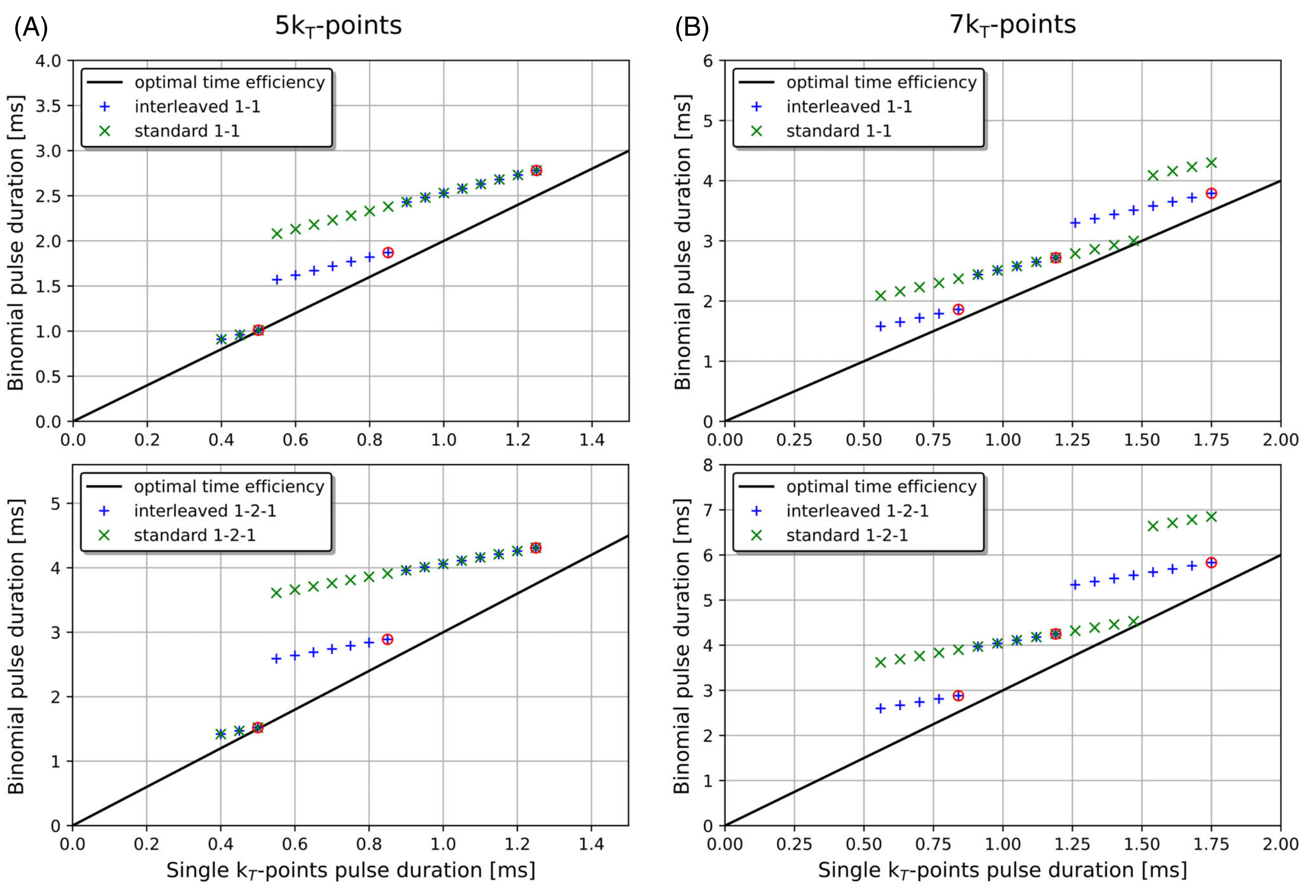

FIGURE 2 Total pulse duration of standard and interleaved binomial k_T-points pulses plotted against the duration of the corresponding non-binomial k_T-points (not water-selective) pulse for (A) 5 and (B) 7 k_T-points. The optimal time efficiency line has a slope of 2 for binomial 1-1 (upper plots) and a slope of 3 for binomial 1-2-1 water excitation (lower plots). Red circles indicate pulses, whose total duration is closest to the optimal case and time is used most efficiently for the interleaved versions. All interleaved binomial k_T-points pulses have the same pulse bandwidth (first root of spectral response at fat frequency) as opposed to almost all standard binomial k_T-points pulses.

nonbinomial k_T-points pulses (not water-selective). Binomial 1-1 or 1-2-1 k_T-points pulses are at least twice or three times as long, respectively. A corresponding line with slope 2 and 3 represents optimal time efficiency, disregarding water-selectivity. The time is used most efficiently when the second (and third) application of the pulse is started directly after finishing the previous application without dead time. Therefore, the RF segments of the binomial water excitation, as defined in Figure 1, should have a duration of $T_{fat}/2$ to use time most efficiently. Figure 2 demonstrates that, if the duration of the RF segment exceeds $T_{fat}/2$, the standard binomial 1-1 water excitation gains T_{fat} in duration, while the interleaved binomial 1-1 water excitation only gains $T_{fat}/2$ in duration. The same applies to binomial 1-2-1 water excitation, where exceeding $T_{fat}/2$ with the single pulse adds 2 times T_{fat} in duration in the standard case and 2 times $T_{fat}/2$ for interleaved binomial water excitation. The most time efficient versions of the interleaved pulses, marked by red circles, are achieved with the longest possible subpulse durations, for a certain number of blocks.

Simulation results for a few selected example pulses are listed in Table 1. In order to get a good compromise between water-selection and homogenization for the RECT water excitation, the number of k_T-points was chosen to be 3, as in Reference 22, resulting in a total pulse duration of 3.29 ms. Then, interleaved binomial k_T-points pulses with subpulse durations leading to the highest time efficiency (red circles in Figure 2) and a basic subpulse duration (50 µs) were chosen. The shortest total durations (1.86 and 1.87 ms) could be achieved with a small number of k_T-points and binomial 1-1 water excitation. However, with short subpulses and therefore increased RF-amplitudes the pulse energy rises, leading to potential SAR problems. Using the proposed interleaved binomial k_T-points 1-1 pulses, the mean fat flip angle increases only slightly compared to the RECT k_T-points pulse, while water is excited more homogeneously (cf. Table 1). By applying interleaved binomial k_T-points 1-2-1 pulses, the mean fat flip angle considerably decreased compared to the RECT k_T-points pulse or binomial 1-1 water excitation.

3.2 | Experiments

The improved flip angle homogeneity of interleaved **binomial** k_T-points pulses was examined in vivo and is shown in Figure 3. Corresponding Bloch simulation results using the B_0 and B_1^+ calibration data confirm that homogeneity increases with the number of k_T-points. The histograms of the Bloch simulations present the flip angle distribution over the brain (the brain outline is drawn in the images with blue), which gets narrower with increasing number of k_T-points. Improved flip angle homogeneity when using more k_T-points is also observed in vivo, using MP-RAGE imaging, especially in the cerebellum. In CP mode, very low signal is measured in the cerebellum and the flip angle drops almost down to zero in some voxels. The 3 k_T-points RECT pulse noticeably improves the image homogeneity throughout the brain compared to CP mode excitation, but still lacks intensity in the lower part of the brain. Interleaved binomial k_T-points (5 or 7 points) achieve better homogeneity than the RECT pulse (3 points) while still having shorter durations.

A comparison regarding the fat suppression quality for a typical fMRI time series acquisition using 3D-EPI is shown in Figure 4. Although the interleaved binomial 1-1 pulse and the RECT k_T-points pulse eliminate most of the fat signal, minor fat artifacts are still present with reduced intensity due to B_0 inhomogeneities (see

TABLE 1 Simulation results of different water-selective pulses. The mean flip angles (FA) were calculated from Bloch simulations based on B_0 and B_1^+ maps of a gel phantom. Type "RECT" is a simple rectangular k_T-points water excitation pulse.[20,22] "B" is the proposed interleaved binomial k_T-points pulse. Remaining excitation inhomogeneity is indicated by the root-mean-squared deviation from the mean (rmsd). The bold-faced parameters are the optimal results from this set of pulses.

Design-Parameters			Resulting parameters			
Type	Number of k_T-points	Subpulse duration (ms)	Total duration (ms)	Water FA rmsd (deg)	Fat FA mean (deg)	Pulse energy (mJ)
RECT	3	1.02	3.29	1.51	0.20	**2.6**
B 1-1	5	0.1	1.87	1.37	0.17	12.1
B 1-1	5	0.05	**1.62**	1.34	0.17	25.9
B 1-1	7	0.1	2.72	**0.98**	0.20	11.3
B 1-1	7	0.05	**1.86**	**0.90**	0.15	20.4
B 1-2-1	5	0.1	1.89	1.45	**0.02**	9.2
B 1-2-1	7	0.05	2.88	**1.02**	**0.02**	15.5

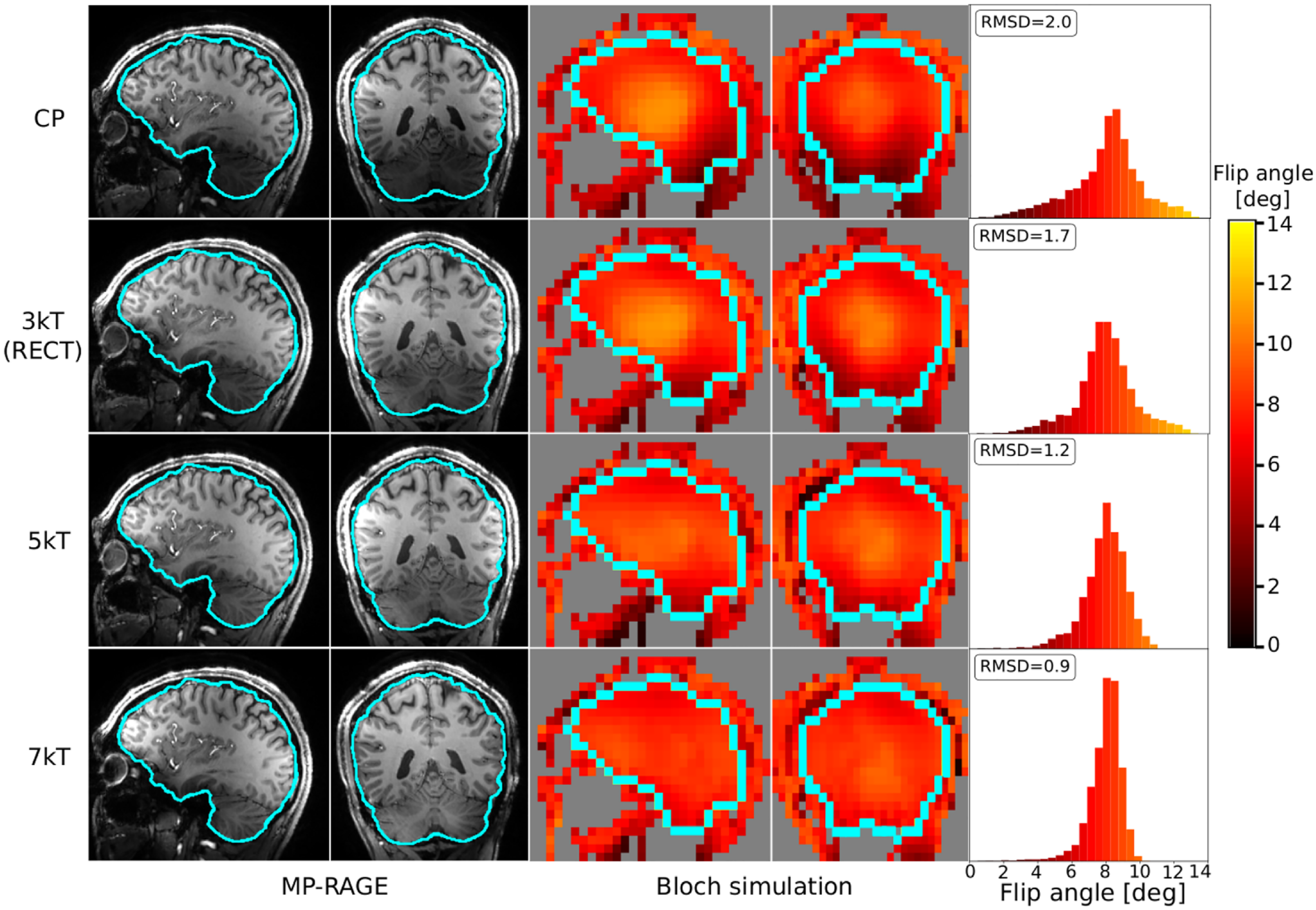

FIGURE 3 In vivo MP-RAGE acquisition with different excitation pulses (circular polarization binomial 1-1 / 3k$_T$ (1020 µs) RECT / 5k$_T$ (100 µs) interleaved binomial 1-1 / 7k$_T$ (50 µs) interleaved binomial 1-1) and respective Bloch simulations. A brain mask (blue line) was extracted from MP-RAGE images and applied to the simulated flip angle maps for histogram generation.

red arrows in Figure 4). When using interleaved binomial 1-2-1 water excitation, which are less sensitive to B_0 inhomogeneities, fat artifacts are mostly suppressed. Two additional subjects were measured with the same setup to demonstrate the robustness of the method and are shown in Supporting Information Figure S1. Both subjects show increased homogeneity with increasing number of k$_T$-points and subject 2 shows improved water excitation quality. Whereas subject 3 has already small fat signal without water excitation such that binomial 1-1 and RECT pulses remove the fat signal from the images.

4 | DISCUSSION

In this work, we proposed a time efficient combination of flip angle homogenization and water excitation for ultra-high field applications. Interleaved binomial k$_T$-points provide an opportunity to circumvent potential weaknesses of binomial pulses when repeating a long pulse after an odd multiple of $T_{fat}/2$. The composite nature of k$_T$-points is utilized to split the pulse in blocks, which are than reassembled to improve the time efficiency and the fat suppression robustness. In most cases interleaved binomial k$_T$-points use time more efficiently compared to the standard version, leading to fewer dead times, where no RF or gradient pulses are applied. Even in cases in which time is not used more efficiently (cf. Figure 2), interleaved binomial k$_T$-points are more favorable due to the insensitivity to off-resonance effects. Standard binomial pulses produce a sinusoidal excitation profile, which is compressed when prolonging the delay between the RF segments, leading to a reduced bandwidth of the minimum. The fat resonance on the other hand is relatively broad,[30] especially in presence of B_0 inhomogeneities, so that fat is not completely suppressed when the spectral excitation profile is compressed. In contrast, interleaved binomial k$_T$-points pulses are designed such, that the first root of their spectral response always matches the fat resonance frequency.

Another advantage of interleaved binomial k$_T$-points, in contrast to the RECT k$_T$-points method,[20,22] are two

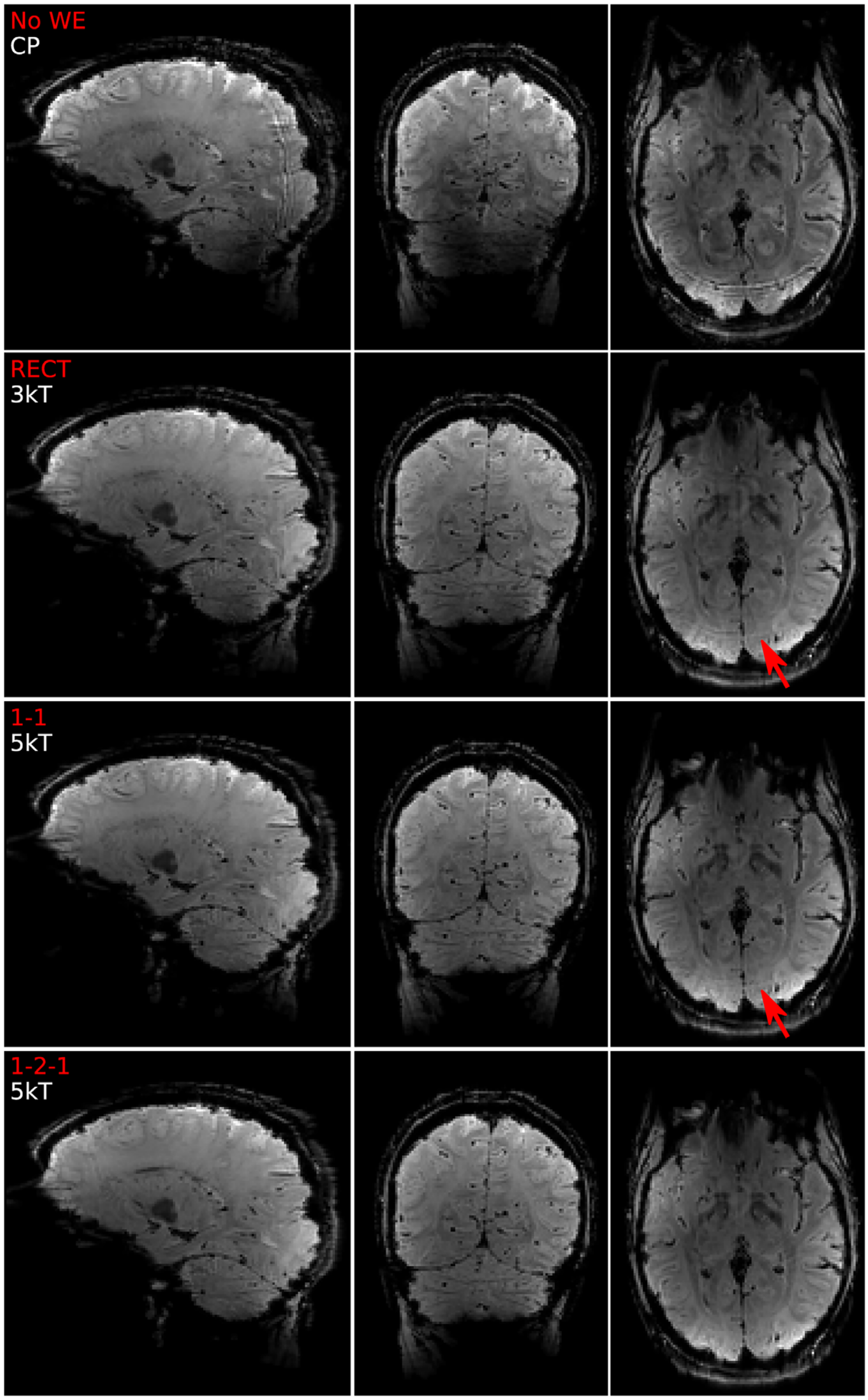

FIGURE 4 In vivo 3D-EPI acquisition with different excitation pulses. Top to bottom: circular polarization mode without fat suppression (No WE), 3 k_T RECT pulse, 5 k_T interleaved binomial 1-1 pulse, 5 k_T interleaved binomial 1-2-1 pulse. Red arrows indicate remaining fat artifacts.

additional degrees of freedom in the pulse design process. For example, one can add more k_T-points and at the same time reduce subpulse durations to maintain the same total pulse durations. However, SAR rises in this case. The number of k_T-points is constrained for RECT pulses, because each additional point adds about 1 ms (at 7T) to the pulse duration, which restricts the homogenization quality. Therefore the proposed interleaved binomial k_T-points were able to reduce the water flip angle inhomogeneity (up to 40% lower) compared to RECT k_T-points[22] and simultaneously achieve shorter pulse durations by 43%, but at the expense of over seven-fold increased pulse-energies compared to the very low energy of RECT pulses. The highlighted values in Table 1 show, that interleaved binomial k_T-points can achieve different goals and a compromise between different parameters can be found depending on individual demands. Binomial 1-1 pulses achieve the shortest durations and can be used if fast RF-pulses are needed. The best fat suppression is achieved by the binomial 1-2-1 pulse, because it has the broadest bandwidth of the nulling frequency and therefore is less sensitive to B_0 inhomogeneities. Although each subpulse block has to be repeated three times, still shorter durations are achieved compared to the RECT pulses. Optimizing the binomial coefficients at water and fat frequencies, as suggested in Reference 24, could provide further improved robustness against B_0 inhomogeneities.

Since the k_T-points pulse is optimized prior to rearranging into binomial water-excitation, universal k_T-points pulses[16] can be simply converted into universal interleaved binomial k_T-points pulses. However, because the pulse gets longer by rearranging the homogenization performance deteriorates for 1-1 and even more for binomial 1-2-1 pulses and B_0 inhomogeneities make more impact. This issue could be addressed by optimizing the pulse after (or simultaneously with) determining the k-space trajectory.

Whether interleaved binomial k_T-points still provide an advantage compared to RECT pulses at even higher static fields (>7T), where the duration of RECT subpulses decreases (to ~760 μs at 9.4T or ~610 μs at 11.7T[31,32]), remains to be shown. Furthermore, SAR rises at higher static fields, which could constrain the subpulse duration of interleaved binomial pulses such that RECT pulses become more favorable.

Since every RF-pulse and every gradient blip can be described as a rotation of the Bloch vector and rotations are not commutative in general, changing the order of subpulses could lead to losses in performance at high flip angles. For small tip angles however, the rotations can be regarded as commutative, because the longitudinal magnetization is considered constant. As binomial pulses rely on the small tip angle approximation,[23,33] interleaved binomial k_T-points are efficient only for small flip angle applications such as segmented 3D-EPI[34] or FLASH.[35] For the 3D-EPI sequence, as used for fMRI, interleaved binomial k_T-points provide the mandatory fat suppression as well as flip angle homogenization at ultra-high fields.

5 | CONCLUSION

We have shown that interleaved binomial k_T-points provide a flexible method to achieve homogeneous whole-brain water-selective small tip angle excitations at 7T. A tradeoff regarding flip angle homogeneity, off-resonance robustness and pulse duration can be found by varying the subpulse duration, the number of k_T-points and the binomial order.

The proposed method presents time-efficient, water-selective, parallel transmit RF excitation pulses for ultra-high field applications. The properties of kT-points are combined with binomial pulses to achieve short, B_1^+ and B_0 insensitive water excitation pulses.

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CONFLICT OF INTEREST

P.L. is an employee of Siemens Healthcare GmbH.

DATA AVAILABILITY STATEMENT

A python implementation of the proposed method can be found at https://github.com/mrphysics-bonn/interleaved_binomial_kTpoints.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

Figure S1. In vivo 3D-EPI acquisitions with different excitation pulses for two additional subjects. Top to bottom: circular polarization mode without fat suppression (No WE), 3 k_T RECT pulse, 5 k_T interleaved binomial 1-1 pulse, 5 k_T interleaved binomial 1-2-1 pulse. Red arrows indicate remaining fat artifacts visible for subject 2. Subject 3 already has little fat signal without water-excitation which disappears with binomial 1-1 or RECT water excitation.

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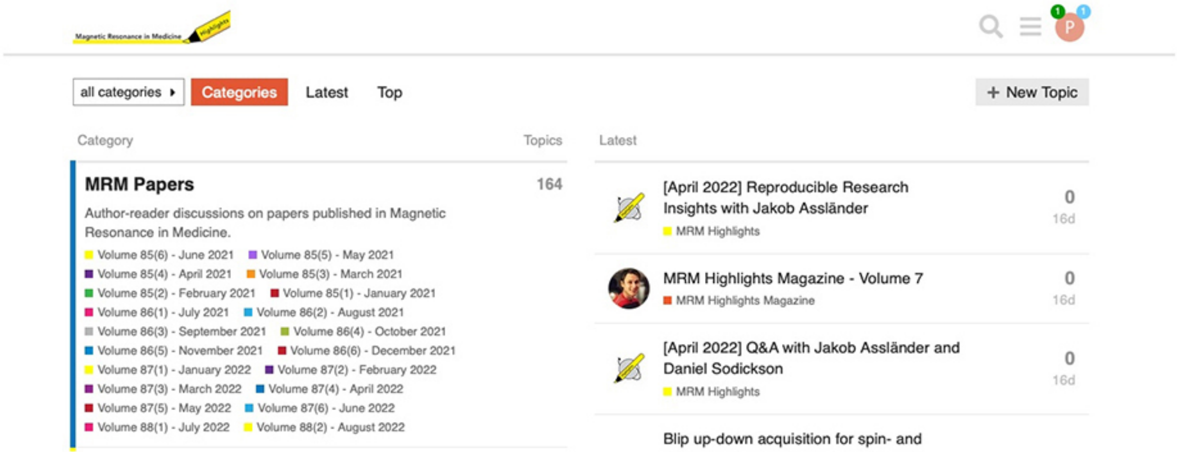

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