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Lowering the B_1 threshold for improved BEAR B_1 mapping

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Abstract

Purpose—Accurate measurement of the nonuniform transmit radiofrequency field is necessary for magnetic resonance imaging applications. The radiofrequency field excitation amplitude (B_1) is often obtained by acquiring a B_1 map. We modify the B_1 Estimation Using Adiabatic Refocusing (BEAR) method to extend its range to lower B_1 magnitudes.

Theory and Methods—The BEAR method is a phase-based B_1 mapping method, wherein hyperbolic secant (HS1) pulses induce a phase sensitivity to B_1 . The measurable B_1 range is limited due to the adiabatic threshold of the pulses. We redesign the method to use flattened hyperbolic secant (HSn) pulses, which have lower adiabatic thresholds. We optimize the HSn parameters to minimize phase sensitivity to frequency variations.

Results—We validate the performance of the new method via simulation and in vivo at 3T, and show that for $n \geq 8$, accurate B_1 maps can be acquired using reduced nominal peak B_1 values.

Conclusion—The adiabatic threshold for BEAR is reduced with HSn pulses, which are optimized for accurate phase-to- B_1 mapping over a frequency range, and allow for lower nominal B_1 values. At 3T the nominal B_1 is decreased by 52% and the sensitivity to B_1 is increased by a factor of 3.8. This can improve the method's applicability for measurement of low B_1 .

Keywords

B_1 mapping; Adiabatic pulses; HSn pulses

Introduction

Mapping of the transmit radiofrequency (RF) field in the form of a B_1 map is important for a variety of applications in magnetic resonance imaging (MRI). A B_1 map can be useful for calibrating the scanner transmit system, evaluating coil performance, and designing parallel transmit excitation pulses (1,2). Accurate B_1 maps are especially important for high main-field imaging ($B_0 > 3T$), where the RF field variations are large due to reduction of the RF wavelength to the order of the sample size (3).

Existing B_1 mapping methods can generally be classified as signal magnitude- or phase-based. Signal magnitude-based methods exploit the use of image signal ratios using different

flip angles (4–6), different repetition times (TRs) (7), stimulated echos (8, 9), and other magnitude B_1 mapping techniques (10–14) to create a signal whose image magnitude maps to B_1 . These methods may suffer from T_1 and T_2 dependence, long scan times, and a limited B_1 range for which the map can accurately be determined. Signal phase-based methods use the relationship between B_1 and image phase to map B_1 , and have used the Bloch-Siegert shift (15), adiabatic pulses (16–18), and other phase manipulation techniques (19,20). These methods may improve the accuracy over a larger B_1 range and insensitivity to T_1 and T_2 , but can require long TRs, be sensitive to B_0 variations, have high specific absorption rate (SAR), and may need phase unwrapping.

The BEAR (B_1 estimation using adiabatic refocusing) method is a recently proposed signal phase-based B_1 mapping method (17) that uses two unequal adiabatic refocusing pulses in a twice-refocused spin-echo sequence, resulting in signal phase that has linear dependence on B_1 , and is insensitive to frequency variation, TR, T_1 and T_2 effects. The method can be localized to a volume, acquire fast projection measurements, and be tuned to a B_1 range by varying the ratio of the adiabatic pulse magnitudes, but has a limited dynamic B_1 range due to the adiabatic pulses' adiabatic thresholds.

We propose a modification to BEAR to lower the nominal B_1 magnitudes used in imaging by replacing the original adiabatic pulses with pulses that have lower adiabatic thresholds. This results in increased phase sensitivity to B_1 . We describe the theory behind the modification and the optimization required to limit otherwise increased sensitivity to frequency variations. We verify the new method's performance with phantoms and in vivo at 3T, and discuss benefits and drawbacks to the method.

Theory

Basic Sequence Using HS_n Pulses

The BEAR method uses two adiabatic full passage (AFP) pulses with different relative magnitudes to create a twice-refocused spin-echo (21–23). Figure 1 shows the original sequence, which uses two hyperbolic secant (HS1) (22) pulses with peak B_1 magnitudes $B_{1,\text{nom}}$ and $\delta B_{1,\text{nom}}$, where $\delta \in [0, 1]$.

Using HS1 pulses, the second echo's phase depends approximately linearly on B_1 while maintaining very little variation over the pulse bandwidth (17). This relationship is only valid for B_1 greater than the sequence adiabatic threshold ($\sim 1/\delta$ times the individual pulse adiabatic threshold), limiting the method's dynamic B_1 range (17). The adiabatic threshold of an AFP pulse ($B_{1,A}$) is the minimum B_1 for which the pulse refocuses the transverse magnetization by keeping it in spin-lock throughout the pulse duration (21), and is defined here as the minimum B_1 that ensures refocusing of 90% $\mathbf{M}_{xy}$.

HS_n pulses offer improved performance for BEAR at lower B_1 due to their reduced $B_{1,A}$ compared to HS1 pulses while maintaining the same average RF power over the pulse bandwidth (24), and can be manipulated to exhibit desired profile characteristics using only a few parameters. The equations governing the magnitude $B_1(\tau, n)$ and frequency $\omega_{\text{RF}}(\tau, n)$ (offset

from resonance) sweeps, and the effective RF trajectory B_1^{eff} of the HSn pulses as a function of n are (24):

$$B_1(\tau, n) = B_1 \text{sech}(\beta \tau^n) \quad (1)$$

$$\omega_{RF}(\tau, n) = \frac{A}{2} - \frac{A}{c} \int_{-1}^{\tau} \text{sech}^2(\beta \nu^n) d\nu \quad (2)$$

$$B_1^{eff}(\tau, \Omega, n) = \sqrt{(\gamma B_1(\tau, n))^2 + (\omega_{RF}(\tau, n) - \Omega)^2} \quad (3)$$

where B_1 is the peak amplitude of the magnitude sweep, $\tau = 2t/T_p - 1$ is a timing parameter given the adiabatic pulse length T_p and $t \in [0, T_p]$, A is the frequency sweep amplitude with the normalization factor $c = \int_{-1}^1 \text{sech}^2(\beta \nu^n) d\nu$, γ is the gyromagnetic ratio, and Ω is the resonance offset of an isochromat. The parameters n and β determine the shape of the sweeps.

Figure 1 shows HSn pulses for $n = [1, 2, 4, 8]$, with the same relative peak B_1 as their respective $B_{1,A}$: as n increases, $B_{1,A}$ decreases. Although the peak power for refocusing 90% M_{xy} decreases as n increases, each pulse's total power remains the same when $B_1 = B_{1,A}$ (24). With HSn pulses replacing HS1 pulses in the BEAR sequence, the sequence $B_{1,A}$ is lowered, increasing the methods' effective B_1 range.

In practice, any value of n can be chosen for each pulse; thus, we use n_1 and n_2 to refer to the value of n for the first and second adiabatic pulses for the solid-line configuration in Figure 1. In general, $n_1 \neq n_2$, and either can be non-integer. The original BEAR sequence is the case when $n_1 = n_2 = 1$.

B_1 Phase Dependence and HSn Pulse Optimization

We use a similar derivation of the phase dependence on B_1 as in (17). Assuming spin-lock, the phase at the end of the pulse sequence is calculated by integrating Equation 3 over each adiabatic pulse in the sequence:

$$\phi(x, \Omega, n_1, n_2) = \int_0^{T_p} \left(\sqrt{(\gamma x B_1(t, n_1))^2 + (\omega_{RF}(t, n_1) - \Omega)^2} - \sqrt{(\gamma x \delta B_1(t, n_2))^2 + (\omega_{RF}(t, n_2) - \Omega)^2} \right) dt \quad (4)$$

where x represents RF field variation, $B_{1,nom}$ is the nominal B_1 of the sequence, with the actual peak $B_1 = x B_{1,nom}$. To eliminate variations in the signal phase unrelated to B_1 , a

second image is acquired with the adiabatic pulse magnitudes temporally reversed. The phase difference of the two images is used to map B_1 , making the phase dependence on B_1 twice that of Equation 4. To eliminate any errors that may result from Equation 4 when $xB_{1,nom} < B_{1,A}$, we use numerical Bloch simulations to determine the phase dependence on B_1 , and to construct a look-up table for mapping phase to B_1 .

Alternatively, the phase dependence on B_1 can be approximated linearly as:

$$B_1(\phi) = a_0 + a_1\phi \quad (5)$$

where a_0 and a_1 are calculated via a polynomial fit of Bloch simulations for on-resonance spins for the expected amount of B_1 variation (Table 1). S_{BEAR} , defined as the phase sensitivity to B_1 above $B_{1,A}$, is approximately $1/a_1$.

BEAR using HS1 pulses ($n_1 = n_2 = 1$, $\delta = [0.48, 1]$), has a nearly flat phase response over the pulse bandwidth. This is important for accurate mapping with through-slice phase using selective adiabatic pulses (as with volumetric imaging) (17), and for off-resonant frequency sources. When $n_1 \neq n_2$, $\delta < 1$, the phase response shows increasing quadratic phase variation compared to that when $n_1 = n_2 = 1$. Both increasing B_1 and changing n results in a change of the quadratic phase. It was determined that this quadratic variation could be reduced by appropriately choosing n_1 and n_2 to alter the amount of quadratic variation from each HS n pulse, over a given range of B_1 . While it is possible that a direct optimization of the adiabatic pulse would yield an improved response compared to this parametric optimization of HS n pulses, such an approach is beyond the focus of this manuscript. Further, we found the parametric approach yielded adequate performance in our experiments. Given a set of sequence parameters $\beta/T_P/A/\delta$ and n_1 , we choose n_2 to cancel the phase variation over a particular B_1 and frequency range by minimizing the numerically calculated maximum percent difference of the phase over the pulse bandwidth from the on-resonance phase, while maintaining constant power. Thus, the SAR for each n_1/n_2 pair equals that of the original BEAR sequence (17), and the phase variation over the bandwidth is minimized. As noted in (17), the SAR for BEAR with $\delta = 0.9$ is comparable to the SAR for the Bloch-Siegert method.

Noise Analysis

We refer to the original BEAR method's noise dependence derivation (17) for the following analysis, which is valid when the phase is linearly dependent on B_1 . The phase standard deviation is defined as $\sigma_\phi = 1/\text{SNR}_{\text{mag}}$ rad, where SNR_{mag} is the magnitude image SNR. Using Equation 5, the B_1 -to-noise ratio $B_1\text{NR}$ is:

$$B_1\text{NR} = \frac{B_1}{a_1} \frac{1}{\sigma_\phi} = \frac{B_1}{a_1} \text{SNR}_{\text{mag}} \quad (6)$$

Note a few important aspects of $B_1\text{NR}$: (1) If $B_1 > a_1$ then $B_1\text{NR} > \text{SNR}_{\text{mag}}$. (2) For $B_1 > B_{1,A}$ and $S_{BEAR} = 1/a_1$, $B_1 S_{BEAR}$ gives the increase of $B_1\text{NR}$ over SNR_{mag} for constant

signal magnitude and sensitivity. Alternatively, given a varying local sensitivity of the phase S as a function of B_1 , B_1S gives the increase of B_1NR over SNR_{mag} for constant signal magnitude. (3) When the signal magnitude varies, e.g. for $B_1 < B_{1,A}$, the B_1NR ratio $M_{xy}/S S_{BEAR}$ indicates how much B_1NR degrades due to decreased sensitivity and magnitude for a particular B_1 (17).

Due to increased phase variation with respect to frequency variations, BEAR using HSn pulses will have increased percent error in B_1 with respect to frequency. The nature of this variation is complex and is not expressed in B_1NR , but is nevertheless examined via simulation below. The sensitivity S will also vary with respect to frequency, potentially resulting in variations of the B_1NR ratio. B_1NR varies with respect to n_1 , n_2 , and the adiabatic pulse parameters.

Methods

Adiabatic Pulse Optimization

The adiabatic pulse parameters, $\beta/T_p/A/\delta$, were chosen in a similar manner as in (17): to minimize $B_{1,A}$ while allowing for reasonable performance with respect to frequency variations. $\beta = 5.3$ rad/s, giving the HSn pulse truncation of $\text{sech}(\beta) = 0.01$, and $T_p/A/\delta = 12$ ms/773 Hz/0.9.

The HSn pulses were optimized for various n_1 and B_1 ranges, because the expected B_1 variation will generally depend on the transmit coil and main-field strength. For each n_1 , a different $B_{1,nom}$ was used for the expected B_1 variation. Table 1 shows optimization results for 3T imaging with $\pm 40\%$ variation in B_1 . Similar optimizations were performed for expected B_1 variations of 20% at 1.5T and 50% at 7T, which are typical variations we observed at these field strengths using head coils. Optimization at 3T gives $B_{1,nom} = [0.1769, 0.1191, 0.0961, 0.0861]$ G for $n_1/h_2 = [1/1, 2/2.034, 4/4.121, 8/8.355]$, with sequence $B_{1,A}S$ corresponding to $[91, 65, 52, 45]^\circ$ tip angles for a 2 ms time-bandwidth product 4 Hamming windowed pulse with 0.117 G peak amplitude. Body coil receive peripheral scans using $n_1 = [1, 2]$ were acquired to test increasing B_1NR by increasing n without decreasing δ . For these scans, the SAR constraint was dropped to keep $B_{1,nom} = 0.1769$ G, giving $n_1/h_2 = [2/2.05]$ for the HSn optimization.

Scanning Parameters

We used a single-slice acquisition protocol on a 3T General Electric (GE) Discovery MR750 scanner. The GE body coil was used for transmission, and a GE birdcage head coil was used for reception except for a peripheral leg scan which used the GE body coil. Informed consent was acquired from all volunteers, in accordance with institutional review board guidelines.

For imaging, a 40° tip angle and $TE/TR = 44/500$ ms were used. TR was chosen to minimize SAR at 3T while providing a relatively efficient scan time. The total scan time was one minute for one slice (two minutes per image pair). For all images, the adiabatic pulses were non-selective, and a single signal acquisition was used. The image matrix size was 128×128 pixels, with a field of view of 24 cm. The spoiler and crusher areas were chosen in the same

manner as (17), with a 1:2 ratio between the crusher areas, and a spoiler area ratio of 1.67 to the smaller crusher.

The BEAR method was also compared in vivo to the phase-based Bloch-Siebert shift method (BS) (15), using an 8-ms Fermi pulse with ± 4 kHz off-resonant frequency, $B_{1,\text{nom}} = 0.0961$ G, TE = 12 ms, and all remaining imaging parameters as previously described.

Results

Table 1 shows optimized values of n_1/n_2 with 40% variation in B_1 , suitable for 3T imaging using a head coil. As n_1 increases, $B_{1,A}$ decreases, while the sensitivity and $B_1\text{NR}$ increase. This decreased $B_{1,A}$ allows for imaging with lower $B_{1,\text{nom}}$ at the price of increased maximum phase error over the pulse bandwidth. If the B_1 variation is above 40%, the expected error increases, e.g., when $n_1 = 4$ the maximum error is 19.6% with 50% variation (data not shown). B_1 can vary approximately 30% from $B_{1,\text{nom}}$ for each n_1/n_2 pair before $B_{1,A}/\delta$ is reached. This percentage of allowable variation changes slightly with n_1/n_2 , since the constraint for constant SAR affects both $B_{1,\text{nom}}$ and n_2 .

Figures 2a–c show Bloch simulation results for BEAR using a set of non-optimized ($n_1/n_2=4/4$) and optimized ($n_1/n_2=4/4.121$) HS n pulses. Figures 2a–b show the magnitude and phase of the refocused M_{xy} as a function of B_1 and frequency. Figure 2c illustrates the signal phase difference over the pulse bandwidth from the 0 Hz (on-resonance frequency) phase, showing reduced phase difference for the optimized sequence compared to the non-optimized case. As with BEAR with HS1 pulses, the phase dependence on B_1 is approximately linear.

Figures 2b–c show the phase error from frequency variations is minimized over the given B_1 range and pulse bandwidth (the black box) for the optimized case, with the maximum error generally located near extreme B_1 and frequency values. Figure 2d shows the maximum phase difference for varying n_1 and main-field strength, indicating 10% or less for all optimizations.

B_1S determines the effect on $B_1\text{NR}$ of a varying phase sensitivity as a function of B_1 , and is shown in Figure 2e as a function of n_1 for on-resonance frequency (solid), and the minimum over the bandwidth (dotted). For $n_1 = [1, 2, 4, 8]$, on-resonance $B_1S = [1.94, 2.73, 3.02, 3.28]$ rad at $B_1 = B_{1,A}$ and $B_1S = [0.529, 0.831, .930, 0.973]$ rad at $B_1 = 0.5B_{1,A}$. When $B_1S > 1$ rad, $B_1\text{NR}$ exceeds SNR_{mag} .

Figure 2f shows the $B_1\text{NR}$ ratio $M_{xy}/S/S_{\text{BEAR}}$ as a function of n_1 for on-resonance frequency (solid), and the minimum ratio over the bandwidth (dotted). This ratio represents the fractional change in $B_1\text{NR}$ due to varying phase sensitivity and signal magnitude. For $n_1 = [1, 2, 4, 8]$, on-resonance $M_{xy}/S/S_{\text{BEAR}} = [1.06, 2.07, 2.88, 3.54]$ at $B_1 = B_{1,A}$, and $M_{xy}/S/S_{\text{BEAR}} = [0.073, 0.213, 0.297, 0.402]$ at $B_1 = 0.5B_{1,A}$.

Figure 3 shows phantom results at 3T for varying n_1 and $B_{1,\text{nom}}$. As a reference for all images, a B_1 map is acquired using the original BEAR method with $n_1 = 1$ and $B_{1,\text{nom}} = 0.1769$ G. Imaging using optimized HS n pulses for decreasing $B_{1,\text{nom}}$ gives comparable B_1

maps to the reference scan, with average absolute differences of [2.09, 2.46, 2.67] % and RMS differences of [0.0235, 0.0268, 0.0289] G for $n_1 = [2, 4, 8]$, $B_{1,nom} = [0.1191, 0.0961, 0.0861]$ G. If $B_{1,nom}$ is lowered while keeping $n_1 = 1$, there is increased difference from the reference scan due to actual B_1 falling below $B_{1,A}$.

The top row of Figure 4a shows in vivo BEAR B_1 maps for $n_1 = [1, 2, 4, 8]$ are all closely match, with $B_{1,nom} = [0.1769, 0.1191, 0.0961, 0.0861]$ G respectively. The bottom row shows percent differences using $n_1 = 1$ for reference. Average absolute differences for $n_1 = [2, 4, 8]$ are [2.89, 2.74, 3.72] % and RMS differences are [0.0395, 0.0357, 0.0441] G.

Figure 4b shows B_1 maps for body coil transmit/receive scans using $B_{1,nom} = 0.1769$ G for $n_1/n_2 = [1/1, 2/2.05]$. The B_1NR for $n_1 = 2$ is 1.38 times that for $n_1 = 1$, resulting in a higher quality map.

Figure 4c shows a comparison of the performance of the BEAR method using $n_1 = 1$ as reference to BEAR using $n_1 = 4$, and to the BS method. The BS map has increased average absolute difference from $n_1 = 1$ compared to the $n_1 = 4$ scan, due to the poor quality of the map near the sinuses for BS. The phase sensitivities for BEAR and BS are also shown for reference.

Discussion

The BEAR method has been redesigned to use HSn pulses, reducing the peak RF amplitude required for accurate B_1 measurement, while maintaining insensitivity to frequency variations across the effective pulse bandwidth, and linear phase sensitivity to B_1 . Additionally, the method's sensitivity to B_1 was increased using increasing n , allowing for a sequence that can be easily tuned for desired performance characteristics. The effective B_1 range of the method depends on several adjustable factors. The lower B_1 limit depends on the adiabatic threshold of the pulses, which is reduced using HSn pulses. The upper B_1 limit can be considered to be the point where the phase difference between acquisition exceeds 2π , although phase unwrapping could be applied in some instances. This upper limit can be increased by increasing δ , which in turn reduces the sensitivity to off-resonance frequency. Scan results show accurate B_1 mapping at lower nominal B_1 . While other adiabatic pulses (e.g., numerically optimized pulses (25)) could be substituted for the original HS1 pulses, the ability to tune HSn pulses with only a few parameters is useful for easily optimizing the sequence for better performance with respect to frequency variations. Furthermore, the HSn pulses used here were found to yield adequate performance in our experiments. Nevertheless, numerically optimized solutions may yield improvements to this method.

To achieve imaging at lower B_1 , we minimized the B_1 map error seen within a given B_1 range by varying the HSn pulse parameters. We found that optimizing for n_1/n_2 had the largest effect on canceling out the quadratic phase variation for a given B_1 ; however, other parameters of the pulses can also be varied ($\beta/T_p/A/\delta$). Our optimizations had a maximum error of 10% for all B_1 ranges. Note that this optimization must be re-calculated for any variation in the sequence parameters ($\beta/T_p/A/\delta/B_{1,nom}$), since these will alter the phase

profile. The range of B_1 that can be mapped using this method depends on the amount of error that is tolerable for the expected B_1 and off-resonance frequency ranges.

As with the original BEAR method, the method's sensitivity can be tuned by varying δ . When using HS n pulses, the sensitivity can also be tuned by varying n_1/n_2 . Because B_1 NR is dependent on the sensitivity of the method, as n_1 increases, the B_1 NR also increases for the same B_1 . To acquire images with the same B_1 NR using different values of n_1 , one would need different numbers of averages for each image. Additionally, as n_1 increases, $B_{1,A}$ decreases, so there is noise reduction due to a smaller range of low B_1 values experiencing very low refocused signal magnitude. Below $B_{1,A}$, the method will experience increased mapping error, especially evident in cases with highly variable B_1 fields (e.g., surface coils). A downside to increasing n_1 is the increased errors due to frequency variations. A balance must be made between B_1 NR, the desired B_1 mapping range, and the amount of error across the effective pulse bandwidth that can be tolerated. When the adiabatic pulses are non-selective, the use of a B_0 map could minimize the error due to off-resonance frequency by using the known phase dependence on B_0 .

Phantom and in vivo B_1 maps were acquired at 3T with low $B_{1,nom}$ and demonstrated similar accuracy as the map acquired with HS1 pulses and higher $B_{1,nom}$. Phantom maps acquired with similarly low $B_{1,nom}$ using HS1 pulses illustrated the effect of measuring B_1 below the adiabatic threshold. The average errors seen in all maps were less than the expected maximum error found via simulation. This is likely from a shim that resulted in much less frequency variation than that allotted for within the bandwidth of the adiabatic pulses. The increasing variation in the difference images matched the expected variation in B_1 NR between the methods.

For the body coil receive peripheral scans, $B_{1,nom}$ is kept near the maximum allowable value to mitigate the effects of very low B_1 on the map. If higher B_1 NR is desired, δ cannot be lowered without potentially increasing the error from the low B_1 ($< B_{1,A}$) measurements. By using HS n pulses, B_1 NR is increased without lowering δ , resulting in a higher quality map.

BEAR performed similarly to the BS method in vivo everywhere except near the sinuses, where large B_0 inhomogeneities affect the BS map. In this region, the BEAR method's spin-echo acquisition refocuses intravoxel phase dispersion caused by B_0 inhomogeneity, thus avoiding the errors present in the BS map. This spin-echo acquisition and linear phase sensitivity to B_1 may make BEAR useful for rapid scanner transmit gain calibration, because a single B_1 volume measurement will closely correspond to the average B_1 of the volume.

Conclusion

The BEAR method has been redesigned to use HS n pulses, reducing the peak RF amplitude for accurate B_1 measurement while increasing the sensitivity to B_1 . The nominal B_1 for BEAR is decreased by as much as 52% and the phase sensitivity to B_1 is increased by a factor of up to 3.8, depending on the value of n_1 used, while maintaining the same allowable variation in B_1 and total RF power. This comes at the cost of increased error with respect to

frequency variations, which was minimized by jointly optimizing the parameters of the two HSn refocusing pulses.

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Figure 1.

The original BEAR sequence uses two HS1 pulses to generate a twice-refocused spin-echo. These HS1 pulses can be replaced with HS n pulses for imaging at lower $B_{1,nom}$, shown in the squared box with increasing n for lighter shades of gray. The refocusing pulses can be made selective in Z or Y for slice- or volumetric- imaging. A second image is acquired with the order of the AFP pulses reversed (dashed lines).

Figure 2.

Simulation results for BEAR using HS_n pulses optimization. Frequency response for **a**: magnitude, **b**: phase, and **c**: percent phase difference from 0 Hz on-resonant frequency for non-optimized $n_1/n_2 = 4/4$ (top row) and optimized $n_1/n_2 = 4/4.121$ (bottom row). Black boxes show the expected B_1 range at 3T, $B_1 = (1 \pm 0.4)B_{1,nom}$, $B_{1,nom} = 0.0961$ G, and the maximum error in the box in (c) is 22.0% for non-optimized $n_1/n_2 = 4/4$ and 7.21% for optimized $n_1/n_2 = 4/4.121$. **d**: Maximum percent phase difference from 0 Hz over the range shown in (c) as a function of n_1 and main-field strength, using optimized values for n_2 . B_1 variations were 20/40/50% for 1.5/3/7T. **e**: B_1S values, indicating $B_1S > 1$ rad for a large range in B_1 . Dotted lines indicate the minimum B_1NR over the pulse bandwidth. **f**: B_1NR ratio as a function of B_1 and n_1 , with the same key as (e). The stars indicated the B_1NR ratio at each $B_{1,nom}$, when the SAR is the same for each n_1 .

Figure 3.

BEAR phantom scan results for varying n_1 and $B_{1,nom}$. Left to right columns have $B_{1,nom} = [0.1769, 0.1191, 0.0961, 0.0861]$ G. The top row shows normalized B_1 maps using the optimized HS n pulses for $n_1/\hbar_2 = [2/2.034, 4/4.121, 8/8.355]$, with percent differences compared to $n_1/\hbar_2 = 1/1$ and $B_{1,nom} = 0.1769$ (used as a reference for all images) in the second row. The third row shows B_1 maps using only $n_1/\hbar_2 = 1/1$, normalized by $B_{1,nom}$, with percent difference compared to $B_{1,nom} = 0.1769$ in the row below. The resulting differences from the reference are summarized in the plot to the left as a function of $B_{1,nom}$, for HS1 pulses (red symbols), and optimized HS n pulses (black symbols). Triangles represent average absolute differences; circles represent maximum absolute differences. For HS1 pulses, the maximum absolute difference is $<18\%$, with average absolute differences of $[4.62, 4.82, 4.21]\%$. For optimized HS n pulses, the maximum absolute difference is $<6\%$, with average absolute differences of $[2.09, 2.46, 2.67]\%$.

Figure 4.

In vivo BEAR results at 3T. **a:** The top row shows acquired B₁ maps for (left to right) n₁/h₂ = [1/1, 2/2.034, 4/4.121, 8/8.355] and B_{1,nom} = [0.1769, 0.1191, 0.0961, 0.0861] G, normalized by B_{1,nom} for easier comparison. The bottom row shows percent differences from n₁/h₂ = 1/1 as reference, with average absolute differences of [2.89, 2.74, 3.72] % respectively. Average absolute differences for five volunteers are also plotted for each value of n₁, with means indicated in red diamonds. **b:** Leg B₁ maps using the transmit/receive body coil with n₁/h₂ = 1/1 (top) and 2/2.05 (bottom) for B_{1,nom} = 0.1769 G. With n₁ = 2 the map quality is improved and has 1.38 times the B₁NR of the n₁ = 1 map, calculated over the gray boxed regions. **c:** In vivo head scans compare the BEAR method with n₁ = 1 and n₁ = 4 to B₁ maps using the BS method, with average absolute differences from n₁ = 1 of [2.66, 11.2] % respectively. The phase sensitivity to B₁ variations for the two BEAR methods (black solid, dashed) and the BS method (gray dotted) is also shown for reference.

Table 1

Optimization results for varying n_1 : Optimized n_2 , polynomial fit values of $B_1(\varphi) = a_0 + a_1\varphi$, $B_{1,\text{nom}}$, $B_{1,A}$, $B_{1,\text{NR}}$, and maximum errors for HS n pulses with $\beta = 5.3$ rad, $T_p = 12$ ms, $A = 774$ Hz, and $\delta = 0.9$ at 3T with 40% variation in B_1 .

n_1	n_2	a_0 (G)	a_1 (G/rad)	$B_{1,\text{NR}}$ (rad)	$B_{1,A}$ (G)	$B_{1,\text{nom}}$ (G)	Max. Error (%)
1	1.000	0.0332	0.0707	2.50	0.107	0.177	0.730
2	2.034	0.0357	0.0320	3.72	0.0765	0.119	4.10
4	4.121	0.0333	0.0219	4.39	0.0612	0.0961	7.21
8	8.355	0.0302	0.0182	4.73	0.0531	0.0861	9.69