Calibration Tools for RF Shim at Very High Field with Multiple Element RF Coils: from Ultra Fast Local Relative Phase to Absolute Magnitude B1+ Mapping

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Introduction:

At very high magnetic field, strong B1 heterogeneities occur in human MR images as RF wavelength becomes equal to, or smaller than, the size of the imaged target, interacting with lossy and dielectric properties of biological tissues(1,2). Different RF Shim techniques can be used in order to mitigate B1 inhomogeneities, which have considerable differences in their respective hardware and B1 calibration requirements, especially with large numbers of elements in a transmit coil array(3). In this study we propose a comprehensive B1 phase shim strategy, considering gradual solutions for increasing B1 Shim demands and for different hardware setups as shown in Table 1. We introduce fast B1 calibration tools utilizing some linear algebra formalism with transmit coil arrays, ranging from simple (relative B1 phase) to more demanding measures (absolute B1 magnitude). We show that local B1 Phase Shim can be performed in less than one minute with a 16 elements transmit coil array, with dramatic gain in local B1+ magnitude.

$$\text{Eq.1}\quad S_{k,j} = R_j \cdot T_k \cdot C = \underbrace{\left|\hat{B}^-_{1,j}\right| e^{i\varphi_j}}_{R_j} \cdot \underbrace{e^{i\varphi_k} \frac{\sin\left(V\left|\hat{B}^+_{1,k}\right|\gamma\tau\right)}{1-\cos\left(V\left|\hat{B}^+_{1,k}\right|\gamma\tau\right)\cdot e^{-TR/T1}}}_{T_k} \cdot \underbrace{M_{z0}\left(1-e^{-TR/T1}\right)e^{-t/T2^*}}_{C}$$

Principle, Methods and Results:

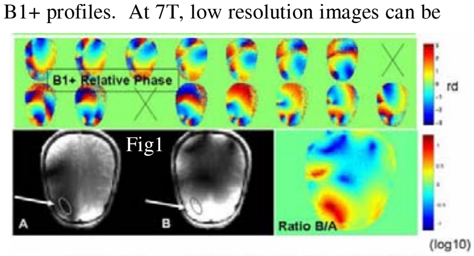
Considering **K** transmit coils k and **J** receive coils j, the complex signal $S_{k,j}$ obtained in receive coil j in a GE image obtained when transmitting with only coil k is shown in Eq.1, where B1- and B1+ are complex transmit and receive B1 vectors with phase φ_j (receive) or φ_k (transmit), and M_{z0} reflects proton density (4). R_j, T_k and C are respectively Receive, Transmit and Common (non coil dependant) terms. Flip angle is given by $\theta_k=V|B1_k^+|\gamma\tau$ where τ is a square pulse equivalent duration. It is important to distinguish between relative phase, relative magnitude and absolute magnitude of $B1_k$+, corresponding to measures A, B and C in Table 1. Note that in this paper, B1+ phase will always refer to the phase in the transverse XY plane.

Table 1. Required Measures and Hardware in RF Shim Techniques

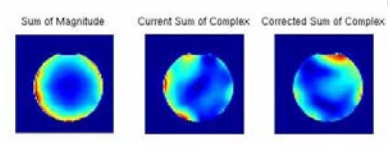
GOAL			NEEDED RF HARDWARE *PER COIL*: Phase Shifter	Magnitude Modulation	Shaped Pulse +RF Amplifier	MINIMUM MEASUREMENT: Relative B1+ Mapping: Phase	Relative B1+ Mapping: Magnitude	Absolute B1+ Magnitude
GOAL	Mapping B1+ Destructive Interferences					+	+	
	LOCALIZED B1+ SHIM	B1+ Phase Only	+			+		
		w/B1+ Magnitude	+	+		+		+
	REGIONAL B1+ SHIM	B1+ Phase Only	+			+		+
		w/B1+ Magnitude	+	+		+		+
	FLIP ANGLE SHIM (2D/3D RF PULSE)	Single RF Coil						+
		Parallel Excitation			+	+		+
						A	B	C

Measure A: Relative B1+ Phase mapping and Local B1 Phase Shim: If one acquires a quick GRE image when transmitting only with one coil, for each coil k (k:1→**K**), and taking k=1 as a reference, it is obvious from Eq.1 that for any receive coil j the phase of the complex ratio $S_{k,j}\div S_{1,j}=T_k\div T_1$ is independent to T1,TE,TR or θ ($\theta<\pi$). Thus, each image can be acquired in less than 3 seconds at Ernst angle for best SNR. Local B1 phase shim then consists in choosing an ROI (a dedicated matlab™ GUI was developed) and computing from the K complex ratios the phase to add to each coil k for all $B1_k^+$'s to be *in phase* at this location. The top row of Fig 1 shows such relative $B1_k^+$ phases at 9.4T (Varian™)in a human brain with 14 transmit/16 receive channels (16 transceiver coil with only 14 available RF amplifiers).The bottom row shows (arrows) the target ROI before (A) and after (B) local B1 phase shim. The Ratio A/B shows a local signal gain of about 20 (log scale). Such phases can be adjusted with as little hardware as various RF cable lengths or passive phase shifters, with only one RF amplifier and a multichannel power splitter. In the case of Fig 1, phase changes were done with a remotely adjustable multi RF amplifier unit (CPC™), so that all results were obtained in less than one minute. Many organs of limited size can already benefit dramatically from such simple approach @7T and above, improving local B1 homogeneity and lowering RF power requirement, thus SAR. This also applies to localized spectroscopy studies.

Measure B: Relative B1+ Magnitude and avoiding "dark holes": Mapping B1+ destructive interference ratio (**DIR**) is useful to determine where, and by which fraction, complex $B1_k^+$'s are cancelling to each other(4). This measure can be obtained with $\mathbf{DIR_j}=|\Sigma_k S_{k,j}|\div\Sigma_k|S_{k,j}|$, which simplifies into $|\Sigma_k B1_k^+|\div\Sigma_k|B1_k^+|$. **DIR** can take values from zero (total cancellation) to unity (no cancellation) (note that R_j and C terms vanish in **DIR** so that, ∀ j, $\mathbf{DIR_j}$~**DIR**). However, two conditions must now be obtained: 1) small flip angles (<10°) must be used to be in a regime where signal intensity is ≈ proportional to flip angle (and thus to |B1+|), and 2) TR chosen accordingly to reduce T1 relaxation bias. In such conditions, simple superposition algebra allows to predict relative destructive interference patterns for any set of $B1_k^+$ phases and magnitudes, and iterative algorithms can be used to avoid or minimize "dark or black holes" in resulting B1+ profiles. At 7T, low resolution images can be obtained in this regime in about 10 seconds per coil in order to not introduce T1 relaxation bias in this index (≈3 times longer than relative phase mapping only, still about only ≈3 minutes for 16 coils). If the conditions above are fulfilled, then, ∀ j: $SK_j=R_j.C.\Sigma_k(T_k)$, which is the sum through K of $S_{k,j}$, is comparable to an image obtained when actually pulsing through all coils together with the reference set of phases an magnitudes and we suggest this verification as an integrant part of standard B1 shim calibration. Fig 2 shows the GUI with, (bottom row) **DIR** before (middle) and predicted after (right) phase adjustment in the center of a phantom @7T.



Measure C: Hybrid Absolute B1+ Magnitude Mapping for multiple Transmit Coils: Although very useful, solutions considered so far do not yet provide flattening B1+ solutions over larger spatial scales (regional/global B1 Shim), which require absolute |B1+| mapping, and it can be reminded that at high field there is no homogenous B1+ volume coil reference. Opposite to the previous requirements for *superposition* formalism, absolute |B1+| mapping requires *sinusoidal* dependence between signal intensity and |B1+|, thus large flip angles, making |B1+| mapping typically very long because T1 relaxation bias has to be avoided (furthermore, T1's are longer at higher field). Some faster techniques have been proposed, but would still remain impractical with a large number of transmit coils. Here we introduce a hybrid approach, consisting in merging the previously collected *relative* information for each coil (*small flip angle linear regime*), with a unique, classic $|B1K^+|$ mapping acquisition obtained when pulsing through all K coils together (*large flip angle sinusoidal regime*). Indeed, for a given set of phase and magnitude: $|B1K^+|=|\Sigma_k B1_k^+|=|\Sigma_k\{|B1_k^+|.e^{i\varphi k}\}|$. Having measured |B1K+| and all $S_{k,j}$'s, it becomes possible to generate each individual coil magnitude with, ∀ j : $|B1_k^+|=\{|S_{k,j}|\div|\Sigma_k S_{k,j}|\}\cdot|BK1^+|$. The image acquisition time to map B1k+ magnitude in a phantom with this technique at 7 Tesla was 16 times 10s (the 16 $S_{k,j}$ data) plus two times 6 minutes (two flip angles for $|B1_k^+|$), which is considerably shorter than mapping $|B1_k^+|$ 16 times. Practically, any B1+ mapping technique could be utilized for the large flip angle case. Knowing $|B1_k+|$ as well as each relative phase φ_k, one can now calculate phase and/or magnitude sets for larger scale B1 shim with appropriate optimization algorithms that are beyond the scope of thia paper. If equipped with multiple shaped RF pulse channels, it is also then possible to utilize Parallel Transmission techniques to obtain a homogenous flip angle within a predefined target with multidimensional RF pulses.



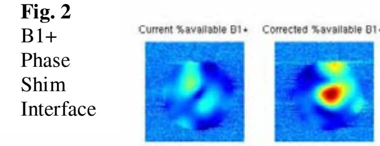


Fig. 2 B1+ Phase Shim Interface

References:1. Vaughan JT, MRM 2001,46:24, 2. Collins C, MRM 1998, 40:847, 3. Adriany G, MRM2005, 53:434, 4. Van de Moortele PF, MRM2005,54:1503,
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