Sa2RAGE - A new sequence for rapid 3D B_1^+-mapping with a wide sensitivity range

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Introduction: At high magnetic field strengths (≥3T) the RF wavelength becomes smaller than the sample size, making transmit magnetic field (B_1^+) inhomogeneity more prominent. RF-shimming [1] and Transmit SENSE [2] have been proposed as methods to minimize this inhomogeneity. To take advantage of these methods it is important to accurately map the B_1^+ field. Saturation prepared with 2 RApid Gradient Echoes (Sa2RAGE) is a new technique which allows the execution of 3D B_1^+-mapping in under a minute with high precision over a 10 fold range of B_1^+.

Methods: Sa2RAGE (Fig. 1) can be seen as a fast saturation recovery sequence with two different delay times. To reduce T_1-sensitivity, the first delay time, TD_1, is kept as short as possible while the second, TD_2, is kept long making the ratio between the two acquired signals $Sa2RAGE_1/Sa2RAGE_2$ mostly dependent on the saturation pulse performance. The predicted Sa2RAGE ratio for several B_1^+ values was numerically calculated after solving the Bloch Equations taking into account the steady state condition. The observed signal was considered to arise from the point where the center of k-space is acquired [3]. From these numerical calculations, a lookup table was established between Sa2RAGE and B_1^+ (Fig. 2). Contrast to noise ratio by unit of time (CNR) of a $B_{1,i}$ estimate was defined as: $(B_{1,i+1} - B_{1,i}) / \sqrt{\sigma_{B_{1,i+1}}^2 + \sigma_{B_{1,i}}^2} / \sqrt{TR_{Sa2RAGE}}$. The noise of the $B_{1,i}$, $\sigma_{B1,i}$, was estimated by error propagation of the noise in $Sa2RAGE_1$ and $Sa2RAGE_2$. Simulations in order to maximize the width of CNR curve (as a function of B_1^+) over an experimentally derived threshold were performed with the following assumptions: (*a*) Number of excitations per GRE module was set to 64 and TR_{Flash} was 2.9ms; *(b)* TD_1 was kept at a minimum value of 101ms; (*c*) T_1 value was assumed to be 1.5s. The parameters varied for optimization purposes were: *(i)* The repetition time $TR_{Sa2RAGE}$ (from 1.4 to 2.6s in steps of 0.2s); *(ii)* TD_2 (from $TR_{Sa2RAGE}$-500ms to $TR_{Sa2RAGE}$ in steps of 50ms); *(iii)* α_1 and α_2 (were varied independently from 1-15°); *(iv)* relative B_1^+ values (from 0.01 to 2.01 in steps of 0.025). In-vitro and in-vivo scans were performed on Siemens 7T parallel transmit (PTx) system equipped with an eight channel transmit-receive array (Rapid Biomedical, Germany). The Sa2RAGE signal was acquired with the following imaging parameters: matrix size of 64x64x16 and resolution of 3x3x5mm^3, taking a total time of 32s. The GRE excitation pulses were slab selective.

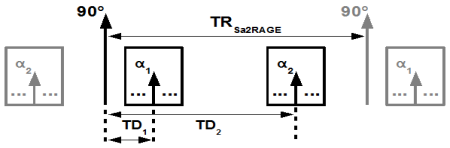

Fig. 1: *Sa2RAGE sequence. A hard nominal 90° RF preparation pulse is followed by two gradient echo blocks with a short repetition time TR_{Flash}. The first and second excitation train have flip angles of amplitude α_1 and α_2. During each block, all nPE2 phase encoding lines of the 2nd dimension are acquired. The sequence is repeated nPE3 in order to acquire all 3rd dimension k-space planes.*

Estimation of interference between different coil B_1^+ maps require the consideration of $B_1^+ = |B_1^+|e^{i\cdot\varphi}$ where φ is the phase of $Sa2RAGE_2$ and $|B_1^+|$ is calculated from the lookup table. To demonstrate the phase sensitivity of Sa2RAGE, eight different modes (all coils, but one, with the same amplitudes and phases combined in CP mode) were excited and individual coil B_1^+ maps were computed by matrix inversion [4] and then compared to B_1^+ maps acquired by single coil excitations.

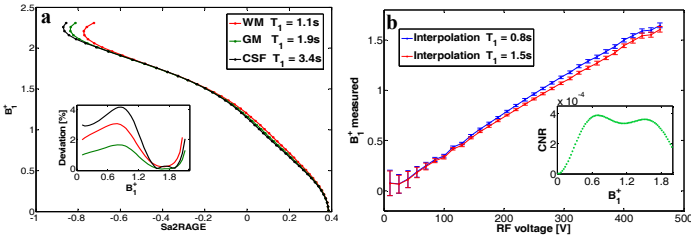

Fig. 2: a. *Dependence of B_1^+ on Sa2RAGE for different brain tissues (the B_1^+ values are presented as relative multiplicative factor of a desired flip angle.* ***Inset:*** *error introduced on the estimated B_1^+ maps for different tissues by considering a fictitious T_1=1.5s.* ***b.*** *Mean values of the B_1^+ field calculated on a ROI (6x7x6 pixels) of the phantom as a function of the transmit RF voltage. Results are close to each other when using different T_1s for interpolation (deviation below 6%).* ***Inset:*** *CNR curve related to Sa2RAGE parameters used for this experiment.*

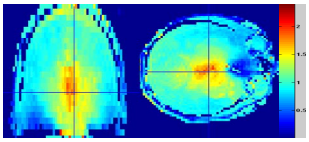

Fig. 3: *Coronal and axial views of a 64x64x24 3D picture acquired with a 3x3x5mm resolution in 48s.*

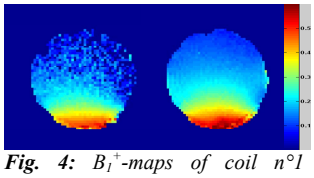

Fig. 4: *B_1^+-maps of coil n°1 located in the array bottom.* ***Left:*** *only coil n°1 excited.* ***Right:*** *matrix inversion of the system all but one coil excited.*

Results and discussion: CNR optimization of B_1^+ sensitivity range provided the following set of parameters for the Sa2RAGE sequence: $TR_{Sa2RAGE}/TD_2/\alpha_1/\alpha_2$=2s/1.6s/5°/13°. As TD_1 cannot be decreased indefinitely, the Sa2RAGE dependence on B_1^+ varies for different T_1s (Fig. 2a); however, for a wide range of B_1^+ values (from 0.21 to 2.11), the deviation curves (inset of Fig. 2a) between WM/GM/CSF and an average T_1=1.5s are always smaller than 5%. To demonstrate the linearity of the B_1^+ estimated by Sa2RAGE with the effective B_1^+ applied, the reference voltage was varied from 10 to 460V in 30 steps. The average estimated B_1^+ in a ROI was measured. Fig. 2b shows the linearity of the estimated B_1^+ values with the amplitude of RF voltage. Furthermore it is possible to see that the noise behaviour is as anticipated from the CNR curve (inset in Fig. 2b). Fig. 3 shows B_1^+ maps performed in-vivo, showing the expected spatial pattern with a central bright spot. It should be noted that underlying anatomy (CSF, GM and WM) is not visible, validating the T_1-insensitivity of the Sa2RAGE sequence. Fig. 4 presents B_1^+ maps of one coil acquired using the PTx system, showing the good spatial agreement between the two methodologies (demonstrating the phase sensitivity of the method).

Conclusion: The Sa2RAGE sequence can be used to map accurately the B_1^+ field within a 3D volume in 32 seconds (potentially 16s if eight slices suffice). It should be highlighted that such short acquisition times did not rely on an EPI readout (that is very sensitive to physiological noise due to inherently longer TE). Other than its speed, it should be noted its wide range of validity, from B_1^+ = 0.2 - 2. The T_1-insensitivity could be increased by using parallel reception, partial k-space sampling or center-out phase encoding schemes in order to reduce TD_1. Sa2RAGE is thus a promising tool for fast and accurate B_1^+-mapping.

References: [1] D. I. Hoult, JMRI 12, 2000, [2] U. Katscher et al. MRM 49, 2003, [3] J.P. Marques et al. Neuroimage, 2009, [4] D. Brunner et al, MRM 61, 2009.
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