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Targeted Radiofrequency Field Mapping using 3D Reduced Field-of-View Catalyzed Double-Angle Method

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Abstract

Purpose—To develop a targeted volumetric radiofrequency (RF) field (B_1^+) mapping technique to provide region-of-interest B_1^+ information.

Materials and Methods—Targeted B_1^+ maps were acquired using 3D reduced field-of-view (FOV) inner volume turbo spin echo catalyzed double-angle method (DAM). Targeted B_1^+ maps were compared with full FOV B_1^+ maps acquired using 3D catalyzed DAM in a phantom and in the brain of a healthy volunteer. In addition, targeted volumetric abdominal B_1^+ mapping was demonstrated in the abdomen of another healthy volunteer.

Results—The targeted reduced FOV images demonstrated no aliasing artifacts in all experiments. Close match between targeted B_1^+ map and reference full FOV B_1^+ map in the same region was observed, with percentage root-mean-squared error $< 0.4\%$ in the phantom and $< 0.8\%$ in the healthy volunteer brain. The abdominal B_1^+ maps showed small B_1^+ variation in the kidneys and liver from the healthy volunteer.

Conclusion—The proposed 3D reduced FOV catalyzed DAM provides a rapid, simple, and accurate method for targeted volumetric B_1^+ mapping, and can be easily implemented for applications related to RF field mapping in small targeted regions.

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Keywords

targeted radiofrequency (RF); field mapping; reduced FOV; inner volume; catalyzed double-angle method (DAM); abdominal MRI

INTRODUCTION

Measurement of spatial distribution of the transmitted radiofrequency (RF) magnetic field (B_1^+) has become an essential but demanding step for many MR applications, such as RF coil testing, RF shimming (1), parallel RF excitation (2), imaging at high field (≥ 3 T) (3,4), and accurate quantitative MR measurements of proton density, T_1 , T_2 , magnetization transfer ratio, and dynamic contrast-enhanced (DCE) MRI pharmacokinetic parameters (5–8).

One common B_1^+ mapping technique is the double-angle method (DAM) (9). This method acquires two images at two different nominal flip angles (α and 2α) and uses the ratio of these two signal magnitudes to derive a B_1^+ map. This method requires complete relaxation of longitudinal magnetization in order to eliminate T_1 dependence (9). Such requirement leads to a long repetition time ($TR \geq 5T_1$) and therefore long acquisition times for DAM. Despite the improvements in time efficiency made possible with various modifications (4,7–9), the DAM is still applied primarily in 2D acquisition modes due to time constraints. 2D acquisition may suffer from non-uniform slice profiles which influence the flip angle calibration and introduce inaccuracies in B_1^+ measurements (10). An additional challenge of 2D acquisition is sensitivity to in-flow effects, which further imposes errors in B_1^+ measurements (6). A B_1^+ mapping technique using 3D acquisition, which produces a superior slice profile and mitigates flow artifacts, is therefore highly desirable. A 3D catalyzed DAM sequence with combination of magnetization catalyzation and multi-echo readout has been recently reported to provide time-efficient and accurate 3D B_1^+ mapping (11). Nevertheless, a 3D acquisition with large volume coverage can still be overly time consuming for routine clinical use.

Fortunately, for many MR imaging applications only a small portion of the field-of-view (FOV) may provide clinically relevant information. For example, during MR temperature mapping to monitor focused ultrasound or radiofrequency ablation procedures, only a small portion of the FOV (position where heat is concentrated) may be of interest to the clinician. During DCE-MRI of tumor perfusion measurements for pre-surgical planning or post-therapy response assessment, only the portion of the FOV that includes tumor and immediately adjacent tissues may be necessary for clinical evaluation. Therefore, for these applications, only information describing the corresponding targeted portion of the B_1^+ in the regions-of-interest (ROI) may be needed. With a reduced FOV acquisition, faster targeted B_1^+ mapping can be achieved with the same spatial resolution. A reduced FOV without aliasing artifacts can be achieved by 1) exciting only the spins inside the desired ROI using 2D spatially-selective RF excitation pulses (12,13) or 2) refocusing only the signals inside the desired ROI using inner volume spin echo (SE), turbo spin echo (TSE), or stimulated echo (STE) sequences (14–16), or 3) suppressing the signals outside the desired ROI using outer volume suppression pulses (17,18). For targeted B_1^+ mapping, the FOV reduction method should be chosen based upon the corresponding RF excitation approach applied for subsequent acquisition of the MR images requiring B_1^+ correction.

This study proposes a targeted B_1^+ mapping technique using 3D reduced FOV catalyzed DAM. Catalyzed DAM introduces a catalyzation pulse chain at the end of each repetition cycle of DAM to drive the longitudinal magnetizations to the same state for both

measurements at two DAM flip angles (11). This added catalyzation pulse chain enables a TR independent of T_1 for B_1^+ imaging. The proposed method employs an inner volume 3D TSE sequence to limit the FOV and thereby shorten image acquisition time. Phantom and in vivo studies are presented to demonstrate the accuracy of this newly proposed targeted B_1^+ mapping approach.

MATERIALS AND METHODS

Sequence Design

The 3D reduced FOV TSE catalyzed DAM sequence defines the inner volume by setting the slab-selective excitation direction to be orthogonal to the slab refocused by the slab-selective 180° refocusing pulse, as shown in Fig. 1. The slab-selective excitation RF pulse (α) with slab selection gradient applied along the slice direction limits the scope of excited spins. Then the following slab-selective (180°) refocusing RF pulses (β) with slab selection gradient applied along the phase-encoding (PE) direction confines the boundary of refocused spins. The intersection of the excitation and refocusing slabs defines the inner volume. Since the 1D spatially-selective RF excitation approach utilized for inner volume imaging is common to most MRI sequences, the reduced FOV catalyzed DAM should be able to provide targeted B_1^+ correction for most MRI applications.

Carr-Purcell-Meiboom-Gill (CPMG) phase cycling schemes ($90^\circ x - 180^\circ y - 180^\circ y - 180^\circ y \dots$) were used for TSE multi-echo acquisition. Crusher gradients alternating in sign and varying in amplitude in the readout direction were applied to preserve only the primary echo pathway and eliminate stimulated echos (11,19). The compensation pulse (δ) and catalyzation chain pulses (θ) are slab-selective and select the same region as the excitation pulse. An RF spoiling scheme with cycled phase was applied consecutively to each compensation and catalyzation chain pulse (11,20). Gradient spoilers, alternating in polarity and varying in gradient moment (11), were also incorporated for each catalyzation pulse along all three axes. The spoiling moments of these gradients after each RF pulse were adjusted to generate a phase distribution of at least 36π within one voxel. An 80-ms duration spoiling gradient along the readout direction is applied at the end of each repetition. This long duration gradient utilizes combined gradient spoiling and diffusion effects (with equivalent diffusion b-value $\approx 8000 \text{ s/mm}^2$) to completely eliminate macroscopic transverse magnetization (21) such that a very short TR (< 5 times T_2) can be used.

DAM Analysis

With successful catalyzation and complete transverse spoiling at the end of each repetition, all other parameters remaining the same and the refocusing flip angle profile neglected, the signal ratio of two TSE DAM measurements at excitation flip angles α and 2α for each voxel is given by (11):

$$\frac{SI_1(r)}{SI_2(r)} = \frac{\sin(C_t(r)\alpha_1)}{\sin(C_t(r)2\alpha)} = \frac{\sin(C_t(r)\alpha_1)}{2\sin(C_t(r)\alpha) \times \cos(C_t(r)\alpha)} \quad (1)$$

where $C_t(r)$ is the flip angle calibration factor.

Therefore

$$C_t(r)\alpha = \arccos\left(\frac{SI_2(r)}{2SI_1(r)}\right) \quad (2)$$

Eq. (2) can be used to derive the spatial distribution of actual flip angle $C_f(r)\alpha$, which is an indirect measure of B_1^+ . With nominal flip angle value α , the flip angle calibration factor $C_f(r)$ can be calculated.

Experimental Studies

All experiments were performed using a 1.5 T clinical MRI scanner (MAGNETOM Espree, Siemens AG Healthcare Sector, Erlangen, Germany). Targeted B_1^+ mapping using 3D reduced FOV TSE catalyzed DAM was first validated in a phantom and in the brain of a healthy volunteer by comparison with full FOV catalyzed DAM (11), and then tested in the abdomen of another healthy volunteer. The study protocol was approved by our Institutional Review Board and written informed consent was obtained from each subject. The body coil was used for RF transmission in all experimental studies. A receiver-only four-channel head coil was used in phantom and brain studies, and a flexible anterior 2-channel phased-array abdominal coil and a 6-channel posterior coil were used in abdominal studies for signal reception. Excitation/compensation, and refocusing pulses were Siemens-equipped RF pulses for SE/TSE sequence. The 90° catalyzation chain pulse was a maximum-phase Shinnar-Le Roux (SLR) pulse (22) with a nominal bandwidth time product of 6 and a duration of 2.56 ms. The slice encoding direction was anterior-posterior for phantom study and cranial-caudal for all *in vivo* studies. The phase encoding direction was left-right for the phantom and brain studies, and anterior-posterior for the abdominal studies. Common imaging parameters of 3D catalyzed DAM (defined in Fig. 1) applied in all the experimental studies were: TE/Tb/Tc = 10.4/10.4/11 ms, excitation/compensation (α/δ) flip angle = 60°/120° and 120°/60°, refocusing (β) flip angle = 180°, catalyzation chain pulse (θ) flip angle = 90°, 3 catalyzation chain pulses, 6/8 partial Fourier in the slice encoding direction, and 50% slice resolution. 15% phase oversampling was applied for all reduced FOV acquisitions. Other varied imaging parameters of 3D TSE catalyzed DAM in different experimental studies were outlined in Table 1.

The accuracy of reduced FOV catalyzed DAM was validated by comparison with full FOV catalyzed DAM in a phantom. The phantom was a bottle of NiCl_2 and MnCl_2 water solution with T_1 of 300 ms measured using an inversion-recovery method. 3D full FOV catalyzed DAM measurements with TR = 2000 ms and reduced FOV catalyzed DAM measurements with TR = 200 ms, co-registered to the same FOV center, were performed for comparison. The scan times were 8 min 46 sec for the full FOV method and 29 sec for the reduced FOV method, respectively. The measured flip angles from reduced FOV catalyzed DAM with TR = 200 ms were compared to the reference flip angle value obtained from full FOV catalyzed DAM with TR = 2000 ms. The percentage root-mean-squared error (RMSE) was calculated within the targeted region of the phantom flip angle map.

The 3D reduced FOV catalyzed DAM was validated *in vivo* in the brain of a 42-year-old female healthy volunteer. Full FOV 3D catalyzed DAM acquisitions with TR = 1000 ms and reduced FOV catalyzed DAM acquisitions with TR = 500 ms, co-registered to the same FOV center, were performed for comparison. The scan times were 9 min 36 sec for the full FOV method and 2 min 22 sec for the reduced FOV method, respectively. The measured flip angles from the reduced FOV catalyzed DAM with TR = 500 ms and full FOV catalyzed DAM with TR = 1000 ms were compared by calculating percentage RMSE within the targeted region of the brain flip angle maps.

A targeted abdominal B_1^+ map covering the kidneys and partial liver was acquired in a 26-year-old female healthy volunteer using 3D reduced FOV catalyzed DAM. A 2D balanced steady-state free precession (SSFP) image was also acquired in the volunteer to demonstrate the anatomic imaging location. The parameters of the balanced SSFP sequence were: 360×180mm² FOV, 256×128 matrix, slice thickness = 5 mm, 16 slices, TR/TE = 3.84/1.92

ms, flip angle = 70° , 560 Hz/pixel bandwidth. Flow saturation bands were applied on both sides of the imaging slab in the slice direction in the abdominal B_1^+ study. The image at each excitation flip angle was acquired separately within an 18-sec breath-hold at expiration position. The *in vivo* 3D abdominal B_1^+ maps were filtered using a 4×4 pixel median filter for each slice.

RESULTS

Fig. 2 shows representative coronal 60° and 120° 3D TSE images of the phantom with full FOV and TR = 2000 ms (Fig. 2a and c), and with reduced FOV and TR = 200 ms (Fig. 2b and d). A good match between full and reduced FOV images in the same region was observed qualitatively. Reduced FOV images demonstrated no aliasing artifacts. Corresponding calculated B_1^+ maps from full and reduced FOV DAM are shown in Fig. 2e and f respectively. The targeted B_1^+ map was well matched to the reference full FOV B_1^+ map in the same region. The flip angle values increased towards the center of the phantom consistent with previous studies (6,10). Flip angle profiles from full FOV and reduced FOV targeted B_1^+ maps through the central line of the phantom were compared in Fig. 2g. Reduced FOV catalyzed DAM measurements closely reproduced the calculated flip angle profile produced with the full FOV method. The RMSE of this targeted flip angle map was $< 0.4\%$.

Fig. 3 shows representative *in vivo* axial human brain 60° and 120° 3D TSE images with full FOV and TR = 1000 ms (Fig. 3a and c), and with reduced FOV and TR = 500 ms (Fig. 3b and d). Again, a good match between full and reduced FOV images in the same region was observed qualitatively except for slightly different contrast due to different TRs used in image acquisition. Reduced FOV images demonstrated no aliasing artifacts. Corresponding calculated B_1^+ maps from full and reduced FOV DAM are shown in Fig. 3e and f respectively. The targeted B_1^+ map closely matched with the corresponding full FOV B_1^+ map. Flip angle profiles from full FOV and reduced FOV targeted B_1^+ maps through the central line of the brain were compared in Fig. 3g. The reduced FOV catalyzed DAM calculated flip angle profile was quite similar to the corresponding full FOV flip angle profile. The RMSE of the targeted flip angle map was $< 0.8\%$.

Fig. 4 shows representative *in vivo* axial abdominal images covering the kidneys and a partial volume of the liver in a healthy volunteer: anatomic balanced SSFP image (Fig. 4a), 60° and 120° reduced FOV TSE images (Fig. 4b and c), and corresponding targeted flip angle map (Fig. 4d). The reduced FOV TSE approach provided good overall image quality and no significant artifacts. The flip angle maps show small spatial B_1^+ variation in the kidneys and liver from the healthy volunteer. The B_1^+ distribution is consistent with previously published abdominal B_1^+ maps (4,23).

DISCUSSION

We have presented a 3D reduced FOV catalyzed double-angle method for rapid targeted RF field mapping. This new approach was validated in a phantom and in the brain of a healthy volunteer, and demonstrated in the abdomen of a healthy volunteer. Reducing the FOV decreases the number of required k-space lines, enabling the acquisition of the same resolution images during a shorter scan time. The FOV restriction here for targeted B_1^+ mapping was provided by the intersection of two separate 1D RF pulses, i.e. a slab-selective excitation RF pulse in the slab selection direction followed by another slab-selective (180°) refocusing pulse in the PE direction. Although this FOV restriction method is not optimally compatible with multi-slice imaging, it is applicable for 3D acquisition and its excitation approach is common to most full FOV MRI applications.

This inner volume mechanism of FOV reduction intrinsically requires a SE/TSE/STE based sequence. The inner volume imaging technique used in this study is naturally compatible with previously developed SE/TSE based catalyzed DAM approaches (11), and can also be combined potentially with other B_1^+ mapping methods, such as SE/TSE version of saturated DAM (4) and SE/STE based method (24). Catalyzed DAM allows the choice of TR relatively independent of T_1 for fast B_1^+ imaging through catalyzation of the magnetization, a process during which the longitudinal magnetizations are forced to the same state for both measurements at two DAM flip angles (11). Based on previous study, the flip angle of excitation/compensation (α/δ) pulses as well as the flip angle and number of catalyzation chain (θ) pulses were optimized in this study to permit a high percentage B_1^+ measurement accuracy for a wide range of flip angle calibration factor (C_1) from 0.6 to 1.5 (11). Nonetheless, the signal-to-noise ratio (SNR) of acquired images is dependent upon the TR. The choice of TR needs to be balanced with SNR, particularly for abdominal imaging applications.

Targeted B_1^+ mapping using inner volume TSE could potentially be affected by the slice profile of the spatially-selective refocusing pulse. In the DAM analysis, we assumed that the refocusing flip angle profile can be neglected from Eq. (1), a logic based on all imaging parameters remaining the same except for the excitation flip angles. Due to the spatial variation of refocusing flip angles across the through-plane dimension of an imaging voxel and its integration effect, Eq. (1) only gives an approximation of the exact signal ratio between two DAM measurements. However, the through-plane variation of refocusing flip angles across a voxel had an almost negligible impact on B_1^+ measurement using 3D acquisition, as validated in our phantom and brain studies, thus Eq. (1) seems a satisfactory approximation. In inner volume TSE B_1^+ mapping, measurement errors from aliasing artifacts can be caused by the refocusing slice side lobes and the transition regions where flip angles fall off towards the edge. 15% phase over-sampling was therefore used in our study to mitigate this problem, and there was no obvious aliasing artifact observed in our experimental reduced FOV images. An outer volume suppression approach could be combined with inner volume TSE to further alleviate the aliasing artifacts, but specific absorption rate (SAR) constraints might then limit imaging speeds particularly at high field strengths (18). A better and sharper refocusing flip angle profile would help overcome the above issues associated with refocusing slice profiles but at the cost of a longer and more sophisticated refocusing RF pulse.

Reduced FOV methods decrease required PE lines, thereby reducing the number of repetition cycles for a fixed echo train length. This reduction could alternatively be translated into reduction of motion and off-resonance induced artifacts (18,25), enabling the achievement of improved image quality and assured B_1^+ measurement accuracy. The k-space reduction of reduced FOV methods depends on the ratio of the desired FOV to the full FOV. In addition, parallel imaging methods can be combined with reduced FOV methods to further reduce the required number of k-space sampling lines. While generally robust, the current *in vivo* targeted B_1^+ mapping using 3D reduced FOV catalyzed DAM occasionally suffered from bulk motion and image mis-registration issues (Fig. 4). Future modification of current reduced FOV catalyzed DAM sequence to be an interleaved acquisition for double angles could help alleviate these motion related issues.

Although this study was demonstrated at 1.5T, identical full FOV TSE based catalyzed DAM has been previously applied at 3.0T within SAR safety limits (11). However, just as with traditional DAM, the presented method may not warrant enough dynamic measurement range for accurate flip angle determination at higher field strength than 3.0T (26). This speaks an obvious limitation of the proposed method.

The Reduced FOV B_1^+ mapping technique can be beneficial for several applications. Targeted B_1^+ information can be used to provide regional correction of transmitter non-uniformities for MR imaging (3); to correct local RF inhomogeneity in T_1 mapping (5,27), T_2 mapping (7), magnetization transfer ratio measurements (8), and quantitative perfusion MRI (28); and to facilitate localized RF shimming within an ROI (29,30). Measurement of local B_1^+ distributions can be sufficient and time-efficient for MR imaging in organs with small cross-sectional size such as the kidney (31) and prostate (29), in organs with long and narrow anatomy such as the spinal cord (25,32), in locations with focused attention such as previously diagnosed tumors during surgical planning or therapy response evaluation, and in targeted treatment regions during interventional procedures (33,34). One particular application for this proposed targeted reduced FOV B_1^+ mapping technique is to provide RF inhomogeneity information in the tumor and surrounding region for quantitative perfusion MRI monitoring of intra-procedural perfusion changes during catheter-directed embolotherapies (35). In clinical setting, rapid targeted 3D B_1^+ mapping can be performed during MRI-guided transarterial chemoembolization procedure (35,36).

In conclusion, 3D reduced FOV catalyzed DAM provides a rapid, simple, and accurate method for targeted volumetric B_1^+ mapping. This study, for the first time to our knowledge, demonstrates a targeted 3D RF field mapping technique using reduced FOV image-based B_1^+ measurements. This technique can be readily implemented for *in vivo* applications related to RF field mapping in small targeted regions.

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Figure 1.

Schematic diagram of 3D reduced FOV TSE catalyzed DAM sequence. $\alpha_{1,2}$: excitation pulse pair. β : refocusing pulse. $\delta_{1,2}$: compensation pulse pair. θ : catalyzation chain pulse. Tb: refocusing and compensation pulse spacing. Tc: catalyzation chain pulse spacing. Note that the slab-selective $\alpha_{1,2}$ excitation pulse selects a slab (slice plane) orthogonal to the slab (phase-encoding plane) refocused by the slab-selective 180° refocusing pulse. Variant crusher gradients in polarity and amplitude along the readout direction were applied for each echo to preserve only the primary echo pathway and eliminate stimulated echos. Variant spoiling gradients in polarity and amplitude are present in slice, readout and phase directions during catalyzation.

Figure 2.

Validation study in a phantom. The phantom was a bottle of NiCl_2 and MnCl_2 water solution with T_1 of 300 ms. (a) The coronal 60° and (c) 120° TSE images acquired using full FOV catalyzed DAM with $\text{TR} = 2000$ ms. (b) The coronal 60° and (d) 120° TSE images acquired using reduced FOV catalyzed DAM with $\text{TR} = 200$ ms. Corresponding calculated (e) full FOV and (f) reduced FOV targeted flip angle maps. (g) Phantom flip angle profiles along central line from full FOV (solid circle) and targeted (solid line) flip angle maps.

Figure 3.

In vivo validation study in a volunteer brain. (a) The axial 60° and (c) 120° TSE image acquired using full FOV catalyzed DAM with TR = 1000 ms. (b) The axial 60° and (d) 120° TSE image acquired using reduced FOV catalyzed DAM with TR = 500 ms. Corresponding calculated (e) full FOV and (f) reduced FOV targeted flip angle maps. (g) Flip angle profiles along central line of brain from full FOV (solid circle) and targeted (solid line) flip angle maps.

Figure 4.

In vivo B_1^+ mapping covering the kidneys and partial liver in a volunteer using reduced FOV catalyzed DAM. a) The axial balanced SSFP image depicting anatomic structure and b) reduced FOV 60° and c) 120° TSE image and d) corresponding calculated targeted flip angle map. The arrows indicate a problematic region in B_1^+ map with low signal intensity (due to air), random visceral motion and image mis-registration.

Table 1

Imaging parameters of 3D TSE Catalyzed DAM in different studies

	Reduced FOV, Matrix size, TR	Full FOV, Matrix size, TR	Echo- train- length (ETL)	bandwidth	Slice over- sampling
Phantom	260×56×40 mm ³ FOV, 128×28×8 matrix, TR = 200 ms	260×130×40 mm ³ FOV 128×64×8 matrix TR = 2000 ms	3	550 Hz/pixel	100%
Brain (Healthy Volunteer)	280×61×80 mm ³ FOV, 128×28×16 matrix, TR = 500 ms	280×157×80 mm ³ FOV, 128×72×16 matrix, TR = 1000 ms	3	550 Hz/pixel	50%
Abdomen (Healthy Volunteer)	360×78×40 mm ³ FOV, 128×28×8 matrix, TR = 400 ms	N/A	4	660 Hz/pixel	50%