Technical Note

Fast B1 Mapping Based on Double-Angle Method with T1 Correction Using Standard Pulse Sequence

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Abstract

Radiofrequency (RF) field (B1) mapping by combining the double-angle method (DAM) and T1 correction was investigated. The signal intensities S1 and S2 acquired by flip angle (FA) α and double FA 2α at short repetition time (TR) were converted to a signal intensity at TR=∞ by T1 correction. Then, these were used for DAM calculation. The T1 values are measured from two different images acquired with different TRs based on the saturation recovery (SR) method preliminarily. The effects of imaging parameters for T1 estimation and measured FA were investigated using $CuSO_4$-doped water phantoms. A two-dimensional gradient echo type echo planar imaging pulse sequence was used. T1 values obtained by the 2-SR method were underestimated compared to the multipoint inversion recovery method. FA error was less than 5% when the appropriate imaging parameters were used. The acquisition time could be shortened to under 25 s by the use of T1-corrected DAM.

Keywords: B1 map, double-angle method, flip angle, radio frequency, T1 correction

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Introduction

Recently, high-field magnetic resonance imaging (MRI) has become widely used. These systems have various benefits, such as a higher signal-to-noise ratio (SNR), higher resolution, and greater spectral separation. However, some technical and physical limitations must be considered when using high-field MRI. One of the major problems is nonuniformity of the radio frequency (RF) field (B1).[1-3]

Although RF transmit calibration is now standard in high-field MRI equipment, the details of RF calibration techniques implemented in clinical scanners are not disclosed to operators, and RF nonuniformity cannot be obtained as an image in most cases.[4,5]

The double-angle method (DAM) is the simplest of the available B1 mapping methods.[6,7] The DAM makes the use of the ratio of the signal intensities of two magnitude images acquired with excitation flip angles (FAs) of α and 2α. These images must be acquired with a long repetition time (TR) to eliminate the effect of T1 relaxation, resulting in longer acquisition times. Although several methods have been proposed for rapid acquisition, operators generally do not take advantage of them in clinical settings, because they require specialized pulse sequences or complex modeling.[8-14]

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In this study, rapid acquisition of B1 maps by combining the DAM and T1 correction measured with a short TR was investigated. The aim was to acquire the maps within a time that would enable breath-holding using general clinical MR equipment and without using a specialized pulse sequence. This was a phantom study and did not involve human participants.

Theory

There is the following proportional relationship between FA α and RF field strength[11]

$$\theta = \gamma B_1 \tau \tag{1}$$

where γ is the gyromagnetic ratio and τ is the RF pulse duration. Therefore, measuring FA pixel by pixel was regarded as B1 mapping in this study.

In a basic DAM, actually irradiated FA θ is calculated using the signal intensity S1 of the image acquired by FA α and the signal intensity S2 of the image acquired by double FA 2α as follows:[6,10,11]

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$$\theta = cos^{-1}\left(\frac{s_2}{2s_1}\right) \quad (2)$$

The FA map can be obtained by calculating θ for each pixel. However, a long TR (TR ≥5T1) is typically used to eliminate the dependence of T1 relaxation, resulting in longer acquisition times. Therefore, S1 and S2 acquired by short TR were converted to those with TR=∞.

The relationship between the signal intensity S of an incoherent gradient echo sequence and the relaxation time can be expressed as follows:

$$S = \kappa.\rho.\frac{\left(1 - e^{-\left(\frac{TR}{T_1}\right)}\right).sin\,\alpha}{1 - e^{-\left(\frac{TR}{T_1}\right)}.cos\,\alpha}.e^{-\left(\frac{TE}{T_2^*}\right)} \quad (3)$$

where k is the scaling factor, ρ is the proton density, TR is the repetition time, TE is the echo time, T1 is the tissue T1 value, T2* is the tissue T2* value, and α is the FA.

If TE = 0, the term exp (-TE/T2*) can be eliminated from Eq. (3) Similarly, if k = 1 and ρ = 1, the signal intensity S_∞ with TR=∞ is calculated as S_∞ = sin α.

The ratio of the signal intensity S_x with TR = x and S_∞ with TR=∞ can be calculated as follows:

$$S_\infty / S_\chi = \frac{1 - cos\alpha.e^{\left(-\frac{TRx}{T_1}\right)}}{1 - e^{\left(-\frac{TRx}{T_1}\right)}} \quad (4)$$

Therefore, it can be converted to a signal intensity of TR=∞ by multiplying the signal intensity obtained by any TR and the above ratio.

However, the tissue T1 value must be known preliminarily to use short TR imaging. The tissue T1 values are measured from two different images acquired with different TRs based on the saturation recovery (SR) method.[15,16]

To achieve the above theory, it requires two images acquired with different TRs at the same FA for T1 estimation and two images acquired with different FAs at the same TR for the DAM. In an attempt to decrease acquisition time, the image was shared between T1 estimation and the DAM. Thus, sufficient images to achieve fast B1 mapping can be obtained by acquiring images under the following three conditions: a short TR with FA α a short TR with FA 2α and a long TR with FA 2α.

Materials and Methods

Effect of imaging parameters for T1 estimation

A pair of short and long TR images acquired with the same FA was used for T1 estimation. The effect of imaging parameters on the accuracy of T1 estimation was investigated.

Four plastic bottle phantoms (diameter, 40 mm; length, 60 mm) were filled with different concentrations of $CuSO_4$-doped water (1, 1.5, 2, or 4 mmol/l [mM]). These phantoms were placed, evenly spaced, in a larger bottle (diameter, 150 mm; length, 90 mm) filled with pure water. These phantoms were considered to cover most of the T1 values of the human body (T1 = 280–2500 ms).

MRI was performed using a 1.5-T MR scanner (Exelart Vantage, Canon Medical Systems, Tokyo, Japan) with a quadrature body coil. A 2D gradient echo type echo planar imaging (EPI) pulse sequence was used (TE = 7.0 ms, number of averages = 1, field of view (FOV) = 250 mm, slice thickness = 10 mm, matrix size = 96 × 96, number of slices = 1). The investigated TR combinations were, (100,500) (100, 1000), (100, 2000), (200, 500), (200, 1000), (200, 2000), (500, 1000), and (500, 2000) ms. For each TR combination, the FA was changed to 30°, 40°, 60°, and 90°, and the number of shots was also changed to 4, 8, and 16.

Signal intensities of each image were measured, and the T1 values of each element of the phantom were calculated according to the 2-point SR (2-SR) method. The region of interest (ROI) was set with a diameter of 35 mm at the center of each element.

Multipoint inversion recovery (m-IR) is one of the most precise means of measuring T1 values.[16] Therefore, the errors of T1 estimation were calculated with respect to the results of m-IR. Imaging parameters of m-IR were as follows: 2D IR fast spin echo, TR = 6000 ms, TE = 10 ms, inversion time = 100, 300, 500, 1000, 3000, and 5000 ms, echo train length = 2, number of averages = 1, FOV = 250 mm, slice thickness = 10 mm, matrix size = 128 × 128, number of slices = 1. A simplex curve-fitting algorithm in the ImageJ public domain software (National Institutes of Health, Bethesda, MD, USA) was used.

All MR images were acquired three times with the same imaging conditions. The error in each element was calculated as follows:

$$error = \frac{(T_1\ 2SR) - (T_1\ mIR)}{(T_1\ mIR)} \times 100\,[\%] \quad (5)$$

where (T1 2SR) is the T1 value measured by 2-SR method, (T1 mIR) is the T1 value measured by m-IR method.

The average of all measurement errors was calculated as the mean error.

Effect of imaging parameters for B1 map

A pair of FAα and 2α images acquired with the same TR was used for B1 mapping. The effect of imaging parameters on the accuracy of FA calculation was investigated.

A large plastic bottle phantom (diameter, 220 mm; length, 350 mm) considering the adult torso was used in this section because the purpose of the FA map is to capture the inhomogeneity of the RF field. The phantom was filled with $CuSO_4$ (1.3 mM) and NaCl (0.9 w/v%) doped water (T1 = 760 ms). This was considered to simulate abdominal organs with longer T1 values in the human body.

The FA map was created by T1-corrected DAM (T1c-DAM) using three images according to the procedure described in the theory section. The investigated TR combinations were the same as previous section. The imaging parameters were also the same as previous section, except for FOV = 300 mm. The total acquisition time to acquire three images for T1c-DAM with several TR combinations is shown in Table 1. For each TR combination, FA was changed to 15°, 20°, 30°, 40°, 45°, 60°, and 90°, and the number of shots was also changed to 4, 8, and 16. Because the DAM requires two images with different FAs, 15°, 20°, 30°, and 45° were used as FA α, which corresponds to 30°, 40°, 60°, and 90° as FA 2 α.

The errors of measured FA were calculated with respect to basic-DAM. Imaging parameters of basic-DAM were as follows: 2D field echo, TR = 5000 ms, TE = 9 ms, other parameters were the same as T1c-DAM. FA maps were generated on a personal computer (MK32M/E-T; NEC, Tokyo, Japan). The processes were performed on a pixel-by-pixel basis with an in-house macro language using ImageJ.

The ROI was set with a diameter of 210 mm at the center of the phantom, and the mean FA value in the ROI was measured. All MR images were acquired three times with the same imaging conditions. The error in each imaging condition was calculated as follows:

$$error = \frac{(FA_{T1c}) - (FA_{basic})}{(FA_{basic})} \times 100[\%] \tag{6}$$

where (FA_{T1c}) is the FA measured by T1c-DAM, (FA_{basic}) is the FA measured by basic-DAM.

The average of all measurement errors was calculated as the mean error.

In addition, to clarify the effect of T1 correction, measured FA values were compared with and without correction. In this comparison, in order to differentiate from basic-DAM, the DAM calculated by FA α and 2 α with the same TR using multi shot EPI was defined as conventional DAM.

Table 1: Total acquisition time for T1-corrected double-angle method

TR (ms)		Acquisition time (s)		
Short	Long	4 shot	8 shot	16 shot
100	500	6	10	16
100	1000	9	15	25
100	2000	16	26	44
200	500	8	12	20
200	1000	11	17	29
200	2000	22	34	58
500	1000	15	23	39
500	2000	22	34	58

TR: Repetition time

Results

Figure 1 shows the average error of T1 estimation due to TR combinations with various FAs. T1 values obtained by the 2-SR method were underestimated compared to the m-IR method. This tendency was marked when the number of shots and FA were low.

Figure 2 shows the mean FA error of T1c-DAM due to TR combinations with various FAs. Measured FAs by the use of T1c-DAM were often overestimated compared to basic-DAM. Overestimation is predominant when the FA α was 15° or 20°. FA error was <5% when the number of shots was 16 and FA α was 45°.

Figure 3 shows representative B1 maps obtained with basic-DAM and T1c-DAM. For T1c-DAM, high FA pair, large number of shots and long TR improve map quality. When the FA 45° used as FA α, it could be seen that FA tended to be higher on the surface of the phantom and lower in the center, as seen in the basic-DAM.

Even if the number of shots 8 or 16 is used, the acquisition time could be shortened to under 25 s by use of T1c-DAM if the appropriate parameters are chosen.

Figure 4 shows the representative comparison of FA measurements with and without T1 correction. The error increases as TR becomes shorter without T1 correction, but it is shown that overestimation can be suppressed even with short TR by T1 correction.

Discussion

In order to perform T1 correction, it is necessary to know the T1 value of the target preliminarily. T1 values obtained by the 2-SR method were underestimated compared to the m-IR method. In order to maintain high accuracy in T1 measurement using the SR method, it is necessary to acquire data at points where the signal intensity changes significantly in the process of T1 recovery. Multipoint measurement is recommended in general, but if the optimum parameters are selected, sufficient accuracy can be provided even with two points.[15] In the 2-SR method, short TR must be chosen at the point of longitudinal magnetization sufficiently suppressed without noise, and long TR must be chosen at the point of longitudinal magnetization sufficiently restored. The optimal combination of the two points depends on image noise, but a long TR is preferably 1.4 to 2 times the target T1 value.[15,16] The phantoms used in the present study were considered to cover most of the T1 values of the human body. The T1 estimation error of the elements that have high T1 values was high because longitudinal magnetization was not restored enough when the short TR combination was used. The lower the FA, the less RF inhomogeneity, but the less the suppression of longitudinal magnetization. Therefore, it is difficult to detect the difference in signal intensity between two TRs. In the first place, if the FA is low, the SNR will be low, and the measurement accuracy will decrease.[15] Short TRs are desired

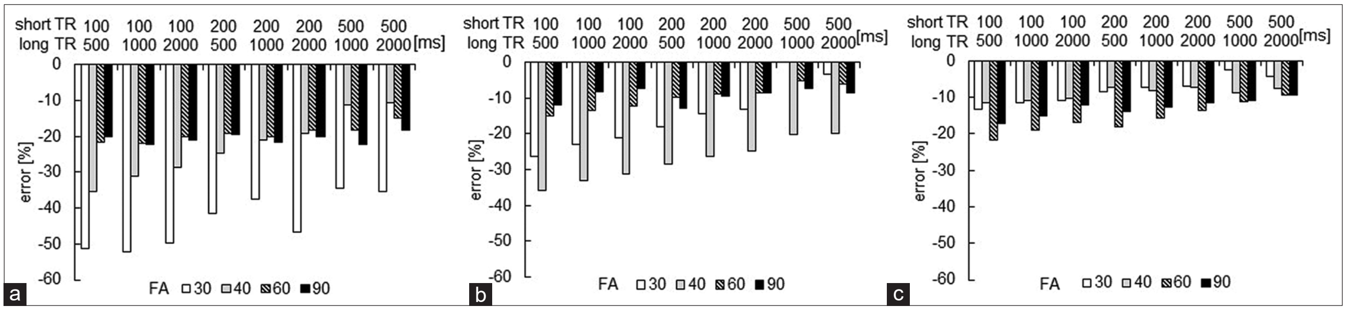

Figure 1: Average error of T1 estimation due to repetition time combinations with various flip angles. (a) Number of shots = 4, (b) number of shots = 8, (c) number of shots = 16. T1 values obtained by the 2- saturation recovery method are underestimated compared to the multipoint inversion recovery method. This tendency is marked when the number of shots and flip angle are low

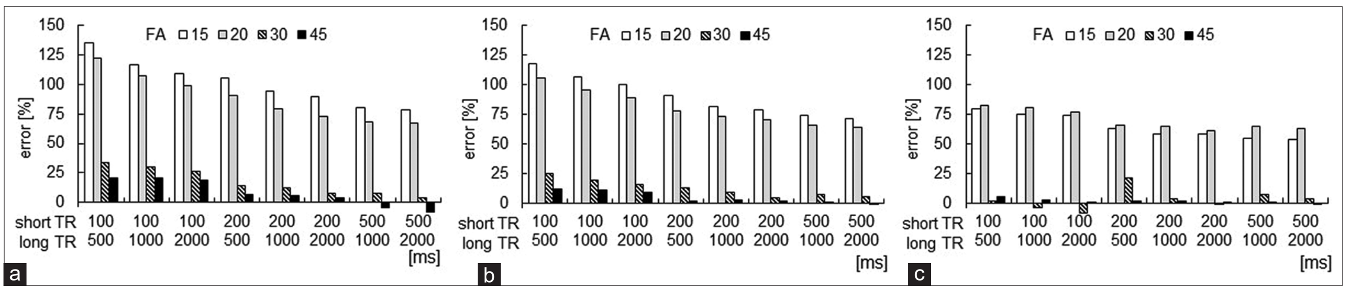

Figure 2: Mean flip angle error of T1c- double-angle method due to repetition time combinations with various flip angles. (a) Number of shots = 4, (b) number of shots = 8, and (c) number of shots = 16. Measured flip angles using T1c- double-angle method are often overestimated compared to basic- double-angle method. Overestimation is predominant when flip angle α is 15° or 20°

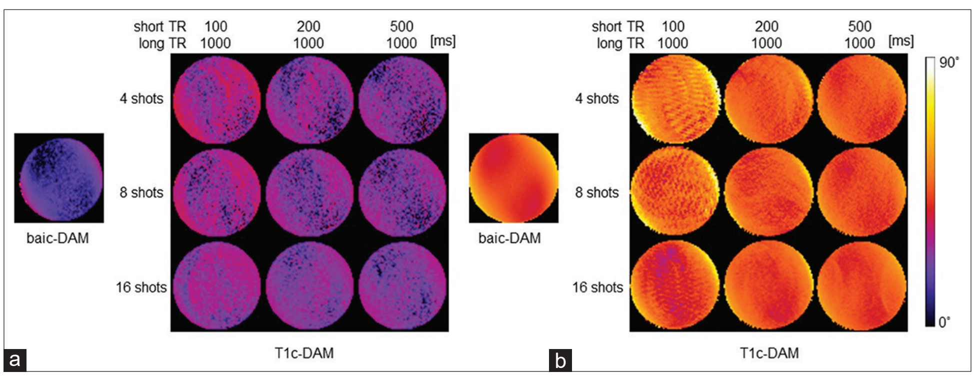

Figure 3: Representative B1 maps obtained with basic-double-angle method and T1c- double-angle method. (a) Used flip angle pair were 20 and 40°, (b) used flip angle pair were 45 and 90°. High flip angle pair, large number of shots and long repetition time improve map quality. In the image (b), it can be seen that flip angle tends to be higher on the surface of the phantom and lower in the center, similar to basic- double-angle method, if the appropriate parameters are chosen

for high-speed measurements, but the Ernst angle must be considered to keep the SNR as high as possible. In addition, the signal intensity used in the T1 estimation was slightly affected by T2* decay because the EPI sequence used in the present study acquired several long TE echo trains. The signal intensity becomes lower due to the effect of T2* decay, and the signal difference between short and long TRs becomes smaller. It is necessary to reduce the echo train to minimize the effect of T2* decay, which is considered to be the reason why the error of 16 shots was smaller than that of four shots. Moreover, it has been reported that the apparent T1 value is shortened in the high-speed measurement.[17,18] This effect is considered to be small in this study because this effect is caused by applying RF at short intervals. However, it may be one of the reasons of the underestimation.

Measured FAs by use of T1c-DAM were often overestimated compared to basic-DAM. Overestimation was predominant when the FA α was 15° or 20°. Since the signal intensities of FAα and 2α are used in the DAM, a large difference between them is preferable, so the FA error when FAα = 45° is generally small. In addition, since the signal intensity is proportional to sin α, low FA is strongly affected by noise. Previous studies have also shown that FA α = 45° has less error in DAM.[19,20] Low FA is not preferable for DAM, similar

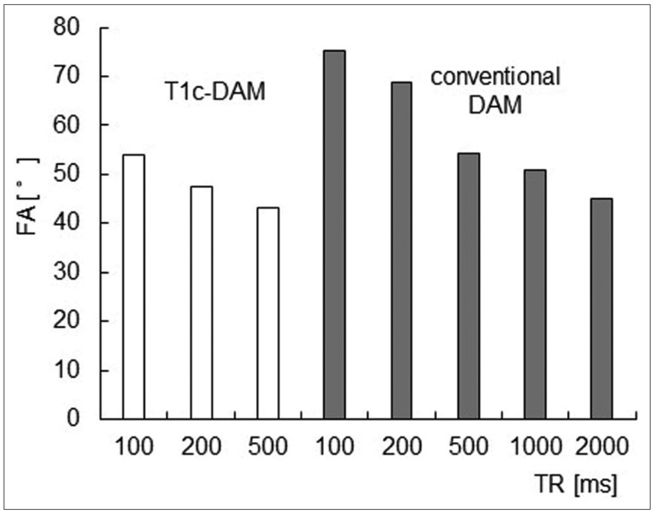

Figure 4: Comparison of measured flip angle between T1c- double-angle method and conventional double-angle method. Although the measured flip angle is expected to be close to the nominal value of 45°, the measured flip angle tends to be larger as repetition time shorten with conventional double-angle method. On the other hand, the flip angle overestimation using T1c-double-angle method remains at a small level. The flip angle pairs used were 45° and 90°, and the number of shots used was 4. In the T1c-double-angle method, the image of repetition time 1000 ms was used as long repetition time for T1 correction

to T1 estimation. The recovery of longitudinal magnetization will be impaired if the TR is short. This effect is greater at the higher FA. Therefore, the signal intensity at a high FA becomes relatively low, and the measured FA can be overestimated according to Equation 2. The T1 value of the phantom used in the present study was set to 760 ms assuming the abdominal parenchyma. The FA error due to TR shortening is expected to decrease if the T1 value is short, and conversely, the error increases as T1 is prolonged because of the SNR decrease.[19] Since the T1 values of muscle and fat are shorter than of this phantom, more accurate measurement can be expected when considering the skin effect.[21] In regard to the number of shots, the larger the number shown, the smaller was the error, as in the case of T1 estimation. However, measured FA by the use of T1c-DAM was almost equivalent to basic-DAM if the appropriate parameters were chosen. Even if the T1 value is underestimated, it is converted to S_{∞} by multiplying the corresponding coefficient of the measured T1 value, so the signal intensities of FA α and 2 α at the converted TR=∞ approach sin α and sin2 α. The accuracy of T1 estimation did not seem to affect the accuracy of T1c-DAM very much. Based on the results, it was considered that multi-shot imaging and keeping the SNR using FA α = 45° are preferable to achieve smaller FA error.

When considering using this technique for abdominal examination, it is preferable to acquire three images within around 20 s for breath-holding. For example, using the number of shot 8 with the TR combination (500, 1000) ms, T1c-DAM can acquire a sufficient B1 map in 23 seconds as shown in Figure 3b. Ghost artifacts were seen in the phantom when the number of shots was 4 or when the TR combination was short. The B1 map obtained with the TR combination (200, 1000) or (500, 1000) ms showed a similar FA distribution to that obtained with basic-DAM, so it seems that it can be sufficiently used for B1 uniformity evaluation. The image quality of T1c-DAM is greatly affected by the imaging parameters, but by using the FA pair of (45°, 90°) and the TR combination that can acquire in approximately 20 to 25 s, the B1 map is comparable to basic-DAM. Although the SNR is lower than basic-DAM, post-processing can improve it, because high resolution is not required for the evaluation of B1 homogeneity.

B1 maps are used in several quantitative MRI applications, such as specific absorption rate estimation, magnetization transfer imaging, and quantitative T1 mapping.[22-24] In addition, quantitative dynamic contrast-enhanced MRI is sensitive to FA errors.[25] In recent years, some numerical methods for computation of RF fields or local tissue temperature have been introduced.[26] However, representative methods for B1 mapping are not easily performed, because they are generally produced using specialized pulse sequences.[8-14] Although the quantitativeness of this technique is limited compared to these studies, B1 maps can be obtained in a shorter time than these by combining multi-shot EPI and T1 correction.[22,27] There was a report that T1 correction is used in B1 mapping, but the purpose of this is to improve the accuracy of B1 measurements rather than rapid acquisition.[28] Recently, MR-compatible implants have become widespread. Even if MRI is performed under the safety criteria, the concern of heating due to local concentration of RF cannot be dispelled, because the heating level depends on the position of the device, the body shape of the subject, and so on.[29] This technique is useful as a method for easily checking RF homogeneity, which could not be routinely confirmed by the MR operators. This technique is expected to be used with a focus on patient safety over quantitativeness.

There are several limitations in this study. The results presented here were obtained using only one 1.5-T MR scanner. A high magnetic field scanner in which B1 inhomogeneity becomes marked was not included in the investigation. Verification at a higher magnetic field will be required. However, B1 spatial variation at 1.5 T is negligible in the human head and musculoskeletal imaging but can be substantial in the torso.[30] In addition, RF nonuniformity is greatly affected by electrical conductivity.[21,31] In consideration of this point, saline was used as the solvent in B1 map validation section, but the electrical conductivity of the human body is not uniform and most of it is lower than the values used in this study.[32] Verification with phantoms of various conductivity will be required. However, the aim of this study is quickly and easily with the same accuracy as the conventional method. Figure 3 shows that the result of the proposed method is comparable to those of the conventional method. Further verification is required due to with the different conductivity, but it is considered that the original purpose has been achieved. It is also noted that EPI is used for the readout scheme. Image distortion occurs easily, and the effects of T2* decay can occur when using EPI.

In this regard, the use of EPI has been reported previously, and the details of readout implementation have little effect on the accuracy of the methods.[10,19,27,33] As already mentioned above, there is concern that accuracy will decrease in tissues with long T1 values. These were the results of phantom experiments, and the accuracy *in vivo* is unknown. In the human body, the effect of fat must be considered, and attention should be paid to chemical shift artifacts. This is almost negligible by use of fat suppression wisely.[10,27] The use of parallel imaging and compressed sensing may also be effective in achieving high-speed imaging.[34,35] However, the aim of this study was to acquire the B1 maps using general clinical MR equipment and without using a specialized pulse sequence. Therefore, EPI with the body coil was used. It is necessary to verify these points in the future.

Conclusion

In this study, the rapid acquisition of B1 maps by the DAM using only the standard pulse sequences that are normally installed in clinical equipment was investigated. By using EPI with shortened TR and converting the signal intensity to that of TR=∞, the accuracy is almost the same as basic-DAM when the appropriate imaging parameters are chosen.

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Nil.

Conflicts of interest

There are no conflicts of interest.

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