TECHNICAL NOTE

Assessment of the Quality of Breast MR Imaging Using the Modified Dixon Method and Frequency-selective Fat Suppression: A Phantom Study

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To obtain objective and concrete data by physically assessing the quality of breast magnetic resonance images based on the fat-suppression effect by the modified Dixon method (mDixon) and frequency-selective fat suppression (e-Thrive) using an original lipid-content breast phantom that could easily reveal the influence of non-uniform fat suppression in breast magnetic resonance imaging. The fat-suppression uniformity was approximately seven times superior when using mDixon compared with when using e-Thrive. mDixon appears to have a significant advantage.

Keywords: *breast, Dixon, e-Thrive, fat suppression, magnetic resonance imaging*

Introduction

In studies conducted using breast MRI, there should be a contrast between the tumor and surrounding tissue. Fat suppression has been recommended to assess contrast enhancement. The image quality (fat suppression, uniformity, etc.) was visually assessed based on a fat-suppression method.[1,2]

In the visual assessment for physical effect, overall evaluation could be performed; however, a mere score was obtained that included subjectivity and relation dependency.

When using physical assessment, scientific, objective, and concrete data could be obtained, and differences depending on the fat-suppression method were remarkable.

In the physical assessment for quantity of non-uniform fat suppressed area, if tissue had complicated structures in the clinical or volunteer images, it was difficult to obtain accurate data from a setting of ROI or threshold point of view.

Fat suppression tends to be non-uniform depending on the individual shape of the breast.[3]

Breast concavities arise from shrinkage due to aging and lead to non-uniform fat suppression.[3] Hyperintensities on MR images may pose a problem in making a clinical diagnosis because when a hyperintensive area is covered with gadolinium (Gd) administration, identifying the mammary lesion could become difficult. To physically assess an image with fat suppression, a breast phantom that could easily reveal the influence of non-uniform fat suppression owing to the shape of concavities could be convenient and quantitative. Therefore, we created an original breast phantom that could easily reveal the influence of non-uniform fat suppression based on clinical data.[3]

In a previous study, to obtain the center frequency, a bottle of copper sulfate was placed between the two breasts of the oil phantom.[3] However, to perform the high-precision physical verification, a lipid-content phantom with a dielectric constant and conductivity similar to that of the human body was needed. Volume shimming is useful to obtain an image with fat suppression. When the frequency offset is optimized for fats in the volume of interest, the effect of fat suppression can be improved.

An effective shimming technique is image-based B_0 shimming (IBS), where the ROI is automatically located along the breast contours[4] during breast MRI. Shimming data are then calculated for the ROI on the B_0 map using IBS. However, fat suppression tends to be non-uniform, depending on the shape of the breasts even, when IBS is used.[3] In a previous report, when volume shimming was optimized, fat suppression became uniform.[3]

Frequency-selective fat suppression with spectral attenuated inversion recovery (SPAIR) is effective because

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an adiabatic pulse is used as a frequency-selective inversion pulse for fats. Hence, fat signals could be suppressed by adjusting the inversion recovery time for fats.[5] Moreover, SPAIR is less sensitive to radio frequency (B_1) inhomogeneity than other frequency-selective fat-suppression methods.[6] Enhanced T_1 high-resolution isotropic volume excitation (e-Thrive) is a 3D imaging sequence that used T_1-weighted gradient echo; it can achieve fat suppression using SPAIR.

Another technique for obtaining an image with fat suppression is the Dixon method,[7] which separates water and fat signals. A modified version of the Dixon method, mDixon[8] is a "two-point" method that renders images by modifying the opposing in-phase and opposed phases of the actual measurement to fit the theoretical value. This method not only obtain four images (in-phase, opposed phase, water, and fat images) in a single scan but also circumvent the limits of the scan parameters because the images can be generated from any pair of phases, with no limitation to the in-phase and opposed phase.[3] Images with fat suppression obtained using breast MRI have reportedly been improved with the Dixon method.[1,2]

Image quality is influenced by noise. Therefore, the contrast-to-noise ratio (CNR) has been found to more accurately reflect tissue differentiation in MRI than mere contrast measurement. The Dixon method creates water-only images with minimal artifacts and an even higher signal-to-noise ratio (SNR) efficiency. mDixon yields a higher SNR and CNR between fats and tumors than e-Thrive.[9] Moreover, CNR is one of the methods for assessing the fat-suppression effect.[9]

To reveal the quality of the fat-suppression effect on the breast MR image, quantitative assessment as an objective physical evaluation is required. However, there have been no reports on comparisons between e-Thrive and mDixon using a breast phantom that could easily reveal the influence of non-uniform fat suppression based on the shape by clinical data.

This study aimed to obtain objective and concrete data by physically assessing the quality of breast MR images based on the fat-suppression effect by the Dixon method and frequency-selective fat suppression using an original lipid-content breast phantom that could easily reveal the influence of non-uniform fat suppression.

Materials and Methods

Because this was a phantom study, Institutional Review Board approval was not required.

Phantom
The outer shell of the original breast phantom, which had a shape that provided images with non-uniform fat suppression based on clinical data, was formed using a thermoplastic sheet for radiotherapy (457 × 559 mm, thickness: 3.2 mm, HipFix Thermoplastic, MTHFX1822S; MEDTEC,
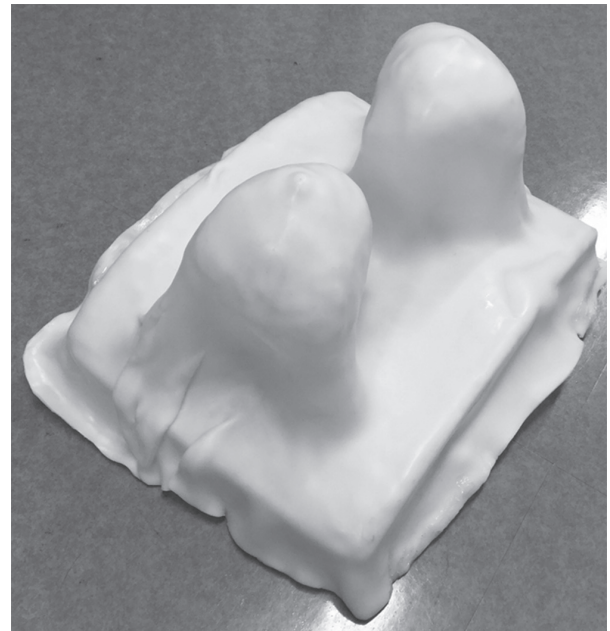
Fig. 1 Outer shell of the phantom.

Inc., DBA CIVCO Medical Solutions and CIVCO Radiotherapy, Coralville, IA, USA). This outer shell was the same as the one used in a previous study[3] (Fig. 1).

The phantom was created with three compartments: one with lipid content, one with T_1 and T_2 relaxation times matching mammary gland tissue, and one with the Gd concentration increased to mimic the signal increase on e-Thrive and mDixon of a post-Gd administration tumor. The phantom included salad oil (as fat), 1500 mL; water, 1500 mL; liquid detergent, 300 mL; and a thickener consisting of 66.67% maltodextrin and 33.33% xanthan gum (Gelespessa; Sosa Ingredients. S.L., Catalonia, Spain), 100 mL. The T_1 and T_2 relaxation times were 549.77 ms and 52.29 ms, respectively. The mammary gland model (gadolinium-diethylenetriamine pentaacetic acid [Gd-DTPA], 0.1 mmol/L; T_1 relaxation time, 1216.9 ms; T_2 relaxation time, 1104 ms) was used. The T_1 relaxation time was referred from the reference data.[10]

About 1 min after administering the contrast medium, the signal intensity was three times higher than the pre-administration intensity.[11] When using e-Thrive and mDixon, the signal intensity of 1 mmol/L Gd-DTPA was approximately three times higher than that of 0.1 mmol/L Gd-DTPA. Therefore, 1 mmol/L Gd-DTPA (T_1 relaxation time, 207.9 ms; T_2 relaxation time, 164.4 ms) was chosen as the tumor model.

MRI
A 1.5T MRI scanner with a seven-channel sensitivity encoding (SENSE) breast coil (Ingenia CX, release 5.2; Philips Medical Systems, Best, Netherlands) was used. The sequence used was e-Thrive (TR, 5.2 ms; TE, 2.5 ms; SENSE factor, 3; flip angle, 15°; matrix, 280; reconstruction

matrix, 432; scan%, 99.61; band width, 360 Hz/pixel; profile order, linear Z; turbo field echo factor, 38; center frequency, 63.884531 MHz) and mDixon (TR, 6.1 ms; TE, 1.96 and 4.0 ms; SENSE factor, 3; flip angle, 15°; matrix, 280; reconstruction matrix, 432; scan%, 78.77; band width, 551.1 Hz/pixel) with the same FOV (280 mm; rectangular FOV, 121.43%), pixel size, $1 \times 1 \times 2$ mm (reconstruction pixel size, $0.79 \times 0.79 \times 1$ mm) (phase × frequency × slice direction), number of slices (150) and scan time (1 min 3 s). Trans-axial images were taken. Volume shimming was optimized to 75/350/50 mm (anterior–posterior/right–left/head–foot direction). The receive gain was consistently maintained, and the scan was performed six times continuously.

Measurement of the non-uniform fat-suppression area

When the non-uniform fat-suppression area was measured, only lipid content was put in the outer shell (lipid-content phantom).

To measure the signal intensity as a threshold, ROIs were set as large as possible in the uniform fat-suppression area of both mamma portions (each portion of approximately 3200 mm^2) in the center of the slice, and pixels of more than the maximum signal intensity (SImax) in ROI were extracted as the non-uniform fat suppression in all slices. The total number of non-uniform fat-suppression pixels in whole slices (a) was calculated using the following equation:

$$axyz = \begin{cases} 1, & axyz > \text{SImax} \\ 0, & \text{(otherwise)} \end{cases}$$

$$a = \sum_{x=1}^{m} \sum_{y=1}^{n} \sum_{z=1}^{o} axyz$$

where "$axyz$" is the number of pixels in the coordinate (x, y) of z slice, "m" and "n" are the number of pixels in an image, "z" is the slice coordinate, and "o" is the number of slices.

Moreover, the non-uniform fat-suppression pixels were summed for the volume data (mm^3) as the non-uniform fat-suppression area. Namely, the volume data was calculated by pixel size ($0.79 \times 0.79 \times 1$) × the number of pixels in all slices (mm^3) (ImageJ 1.50i; National Institute of Health, Bethesda, MD, USA). The mean value and standard deviation (SD) was calculated from six-time scanning.

Measurement of the CNR

The mammary gland model and tumor model were fed into the right and left mamma portions of the lipid-content phantom and scanned. Regions of interest (approximately 320 mm^2) were set in the right and left mammary gland model and tumor model and four points of the fats of the center slice image (Fig. 2). Signal intensities were measured in every ROI in the right and left portions. The signal intensities of the four ROIs of the fats were averaged.
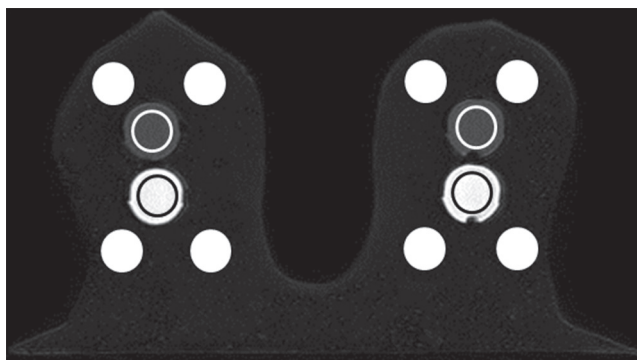
Fig. 2 Measurement of the contrast-to-noise ratio (CNR). The mammary gland model and tumor model were fed into the right and left mamma portions of the phantom and scanned. The ROIs (approximately 320 mm^2) were set in the right and left mammary gland model (white circle) and tumor model (black circle) and four points of the fat (white filled circle) of the center slice image. The signal intensities were measured in every ROI in the right and left portions. The signal intensities of the four ROIs of the fat were averaged. CNRs were calculated by the signal intensities and the standard deviation (SD) of the tumor model.

Contrast-to-noise ratios were calculated according to the following equations:

$$CNR_1 = | \text{SIt} - \text{SIf} | / \text{SDt} \qquad (1)$$
$$CNR_2 = | \text{SIt} - \text{SIm} | / \text{SDt} \qquad (2)$$

where SIt is the mean value of the signal intensity of the tumor model, SIf is the average value of the mean signal intensities of fats in the four ROIs, SIm is the mean value of the signal intensity of the mammary gland model, and SDt is SD of the tumor model.

Measurement of the noise of the air was prevented using parallel imaging[12] (i.e., SENSE). Furthermore, higher-signal intensity areas show fewer accidental errors when SDs are calculated for them.[12] Therefore, the SD of the tumor model (having higher signal intensity) was chosen. The calculations were performed using the ImageJ software. The mean value and SD of CNR were calculated from six-time scanning.

Statistical analysis

For the comparison between e-Thrive and mDixon, the Wilcoxon signed-rank test was used for statistical analysis ($P = 0.05$) (JMP Pro v. 11.1.1; SAS Institute Inc., Cary, NC, USA).

Results

Measurement of the non-uniform fat-suppression area

Interior fat suppression between the right and left breast portions was remarkably less sufficient when using e-Thrive than when using mDixon (Figs. 3 and 4). Along the phantom surface, higher signal intensity was achieved using mDixon (Fig. 4b). The fat-suppression area was approximately seven
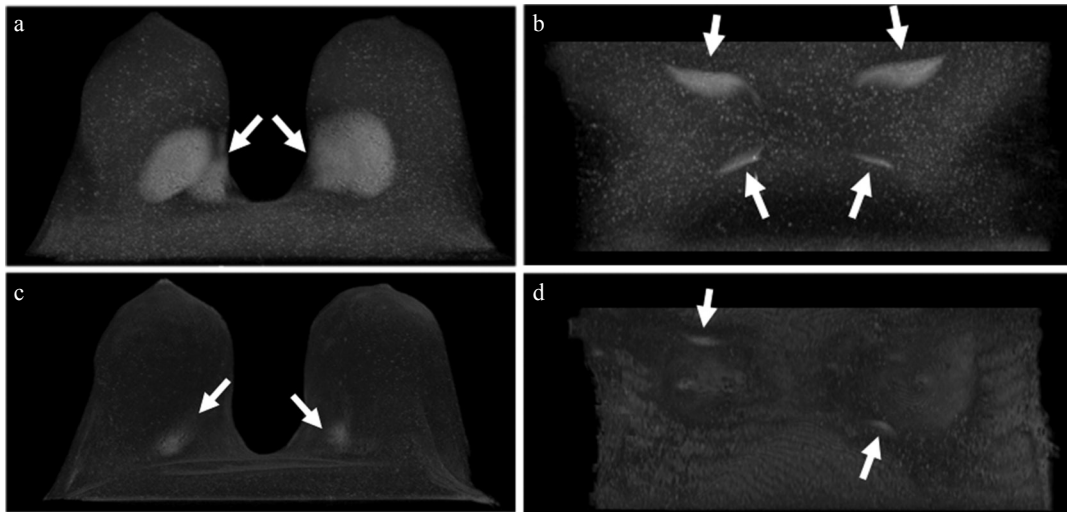
Fig. 3 Images of maximum intensity projection. Interior fat suppression between the right and left breast portions was remarkably less sufficient when using enhanced T$_1$ high-resolution isotropic volume excitation (e-Thrive) (**a** and **b**) than when using the modified Dixon method (mDixon) (**c** and **d**). Images were depicted by head–foot direction (**a** and **c**), and anterior–posterior direction (**b** and **d**).
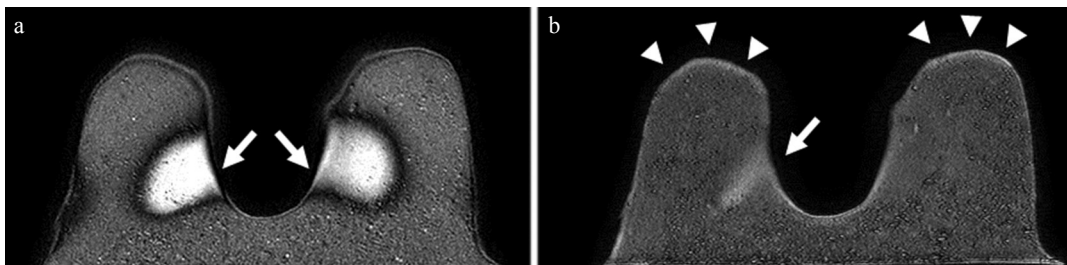
Fig. 4 Sample images of the non-uniform area. Images were obtained from the 42nd slice of 150 slices from the top. Non-uniform fat suppression areas were found when using enhanced T$_1$ high-resolution isotropic volume excitation (e-Thrive) (arrows) (**a**). Along the surface of the phantom, higher signal intensity was achieved by using the modified Dixon method (mDixon) (arrowheads) (**b**).

times larger when using e-Thrive (37785.74 ± 405.27 mm^3) than when using mDixon (5486.16 ± 227.69 mm^3). There was a significant difference ($P = 0.031$) (Fig. 5).

Measurement of the CNR
The CNR using mDixon was significantly higher than that using e-Thrive. The statistical difference in CNRs between the tumor and fats (mDixon, 58.37 ± 5.48; e-Thrive, 51.25 ± 4.01) was $P = 0.016$ and between the tumor and mammary gland (mDixon, 46.53 ± 4.51; e-Thrive, 36.89 ± 2.81) was $P = 0.031$ (Fig. 6).

Discussion

A visual assessment for diagnosis is needed in actual clinical setting. Although images had different physical indices, the assessment of superiority or inferiority in the clinical study was difficult when the images were not visually different. Moreover, when images had considerable noise, the difference in the contrast could not be visually differentiated even with high-contrast physical assessment, thereby producing low scores. Furthermore, visual assessment could be useful in the
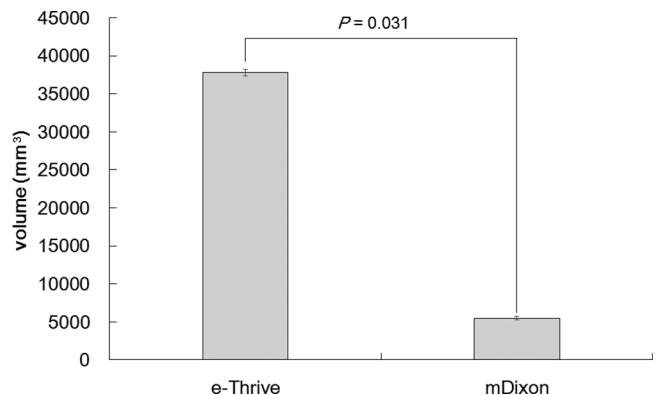
Fig. 5 Results of the measurement of the quantity of the non-uniform fat-suppression area. The quantity of the insufficient fat-suppression area was approximately seven times larger when using enhanced T$_1$ high-resolution isotropic volume excitation (e-Thrive) than when using the modified Dixon method (mDixon). There was significantly difference ($P = 0.031$).

assessment of diagnostic ability or overall image quality as the setting of ROI was difficult because of complicated tissue structures in clinical images. These included detectability,
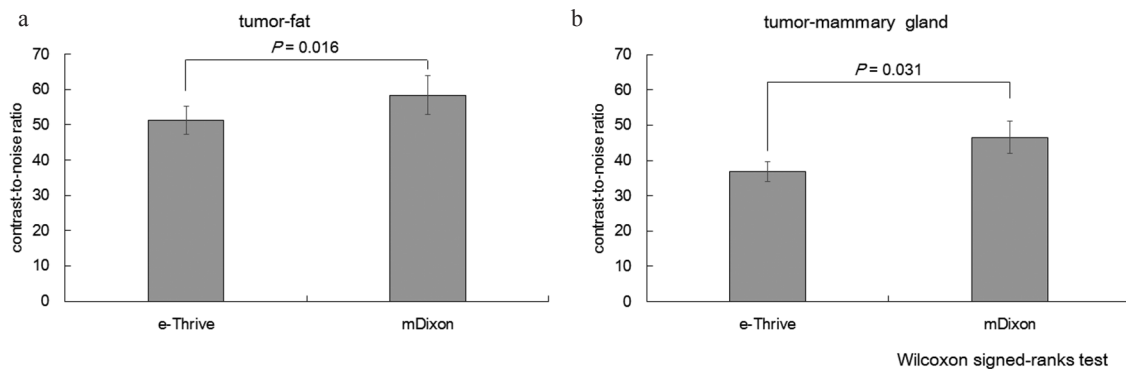
Fig. 6 Results of the measurement of contrast-to-noise ratio (CNR). The differences in the CNRs between tumor and fat was $P = 0.016$. The CNR of the modified Dixon method (mDixon) was approximately 1.1 times higher than that of enhanced T_1 high-resolution isotropic volume excitation (e-Thrive). (**a**) The differences in the CNRs between tumor and mammary gland was $P = 0.031$. The CNR of mDixon was approximately 1.3 times higher than that of e-Thrive. These were significantly different.

accuracy, and sensitivity. Thus, we considered that not only physical index be used for image assessment but also visual assessment.

However, we focused on physical effects used by the phantom image, and physical assessment could be convincing for physical effects. In this study, purely objective data was obtained by physical assessment. We considered that objective data could be convincing, for example, showing the concrete difference instead of a mere score by visual assessment. We found that the fat-suppression uniformity was approximately seven times superior when using mDixon compared with when using e-Thrive. mDixon appears to have a significant advantage in breast MRI studies. The above-mentioned finding was scientifically proved.

In the physical evaluation of the breasts, phantoms are useful because they provide consistency and avoid stress associated with examination periods. To confirm the signal intensity, SNR, CNR, and B_1 map depending on a sequence parameter in breast MRI, phantom study was useful. However, when non-uniform fat suppression is evaluated, the shape of the breast should be noted.

Moreover, when uniform fat suppression is assessed depending on a sequence, a phantom with non-uniform fat suppression based on clinical data is required. Therefore, using an appropriate phantom, we believed that the high-precision physical assessment should be performed using a lipid-content phantom instead of previous studies' data.[3] We considered that the original lipid-content phantom had a dielectric constant and conductivity more similar to that of the human body than the oil phantom. Furthermore, our original phantom was easy to influence the non-uniform fat suppression; therefore, characteristics and differences between two fat-suppression methods were remarkable with respect to the fat-suppressed effect. Furthermore, we believed that we could perform highly reliable comparisons of fat-suppression methods in near-clinical situations.

Concavities led to a wide contact area between the surface and the surrounding air, thereby influencing fat

suppression.[3] During breast MRI, if the surface area in contact with the air is wide, the magnetic field tends to be non-uniform, and the center frequency is shifted. Therefore, fat suppression was non-uniform when using e-Thrive.

The reason why high signal intensity was obtained at the surface of the phantom using mDixon is that the separation between fats and water was miscalculated between the phantom and the surrounding air. However, the non-uniform fat saturation area using mDixon was smaller than that using e-Thrive. Depicting the tumor and making an accurate diagnosis could be influenced if non-uniform fat-suppression area overlapped the tumor. We found that mDixon provided an advantage in the acquisition of data used for diagnosis in breast MRI.

The CNR of a lesion when using the Dixon method has been found to be higher than that when using frequency-selective fat suppression.[1,2] Therefore, we believe that mDixon detects mammary lesions with a high detectability rate. When using mDixon, to minimize non-uniformity of the local magnetic field, a calculation using an equation with B_0 was performed.[8] We found that mDixon provided higher accuracy than e-Thrive by enabling better correction in the non-uniform area. The modified Dixon method does not suppress any signals; instead, it separates water and fat signals. Our results correspond to those previously reported.[9] We found that mDixon provided a higher CNR than e-Thrive.

Generally, threshold setting is used in binarization. Discriminant analysis is used when the contrast between the target area and background is clear. When the target area is smaller than the background or when there is little intensity change, Laplacian or differential histogram methods are used by setting a border between the target area and background. However, the border between uniform and non-uniform fat-suppressed areas was unclear, irregular, and with wide gradation. Therefore, an incorrect threshold determined by the above-mentioned methods may result in segmentation error; underestimation of the non-uniform fat-suppressed area may

also be observed. Our method could sufficiently extract all non-uniform fat-suppressed areas, thus, proving its validity.

A limitation of this method is that the results arising from the calculation of the volume data may have been influenced by the size and position of the ROI. However, we believe that the differences in the non-uniform areas between the two fat-suppression methods were similar, because the ROI size and position in the same slice were similar in both the settings; thus, the data in this study could be highly reliable.

Another limitation of this study was that patients were not included; therefore, variations in the characteristics of tumors (e.g., vascularity or presence of fats) were not assessed. We did not assess the influence of implants, such as metal or silicon. Moreover, we did not evaluate the dependence of the Dixon method on sequence parameters (dependence on the number of points). Therefore, further study might be needed. However, using a phantom helped provide consistent conditions for our comparison of the two methods; thus, objective, concrete, and convincing data was obtained.

Conclusion

The physical assessment of the quality of fat-suppression effect in breast MR images with the Dixon method and frequency-selective fat suppression using an original breast phantom that could easily reveal the influence of non-uniform fat suppression was objectively and concretely evaluated. The fat-suppression uniformity was approximately seven times superior when using mDixon compared with when using e-Thrive. mDixon appears to have a significant advantage in breast MRI studies.

Conflicts of Interest

All authors declare that there is no conflicts of interest.

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