

Improved breast cancer characterization with high-resolution 3D T2-weighted image at equivalent scan times to conventional 2D fast spin echo T2-weighted image

Kazushige Ichikawa¹, Hiroko Satake², Mami Iima³, Satoko Ishigaki²,
Yutaka Kato¹ and Shinji Naganawa²

¹Department of Radiological Technology, Nagoya University Hospital, Nagoya, Japan

²Department of Radiology, Nagoya University Graduate School of Medicine, Nagoya, Japan

³Department of Fundamental Development for Advanced Low Invasive Diagnostic Imaging, Nagoya University Graduate School of Medicine, Nagoya, Japan

ABSTRACT

This study aimed to optimize three-dimensional T2-weighted image (3D T2WI) to match 2D T2WI scan times in a phantom study and compare their image quality and diagnostic potential in clinical breast magnetic resonance imaging (MRI). A phantom study evaluated contrast-to-noise ratio (CNR) and spatial resolution using four spheres mimicking cyst, benign tumor, malignant tumor, and fibroglandular tissue (FGT). CNR was compared between variable refocusing flip angle (VRFA) and constant FA approaches across equivalent echo times (TE) of 80–120 millisecond (msec). Optimal resolution was assessed using voxel sizes of $1.1 \times 0.8 \times 2.0$ (2D) and $1.0 \times 0.8 \times 1.4$, $0.8 \times 0.6 \times 1.4$, $0.7 \times 0.5 \times 1.4$ mm³ (3D) with equivalent TEs of 100–120 msec. Seventy female patients were included in this Nagoya University Hospital Institutional Review Board (IRB)-approved retrospective study. Signal-to-noise ratio (SNR) and CNR between lesions and FGT were calculated. Two radiologists independently evaluated all T2WIs using a 5-point Likert scale. 3D T2WI with VRFA consistently provided higher CNR than constant FA. CNR between malignant tumor- and FGT-mimicking spheres, and between benign tumor- and FGT-mimicking spheres peaked at equivalent TE of 100 msec. Optimal balance between resolution and equivalent TE was achieved with $0.8 \times 0.6 \times 1.4$ mm³ and 100 msec. Lesion SNR showed no significant difference between 2D and optimized 3D T2WI (6.23 ± 2.83 vs 5.96 ± 2.84 , $p > 0.05$), nor did FGT SNR (6.59 ± 3.00 vs 6.33 ± 3.38 , $p > 0.05$). However, optimized 3D T2WI demonstrated significantly higher CNR (4.15 ± 3.11 vs 3.62 ± 2.74 , $p < 0.05$) and superior radiologist scores across all criteria ($p < 0.01$). Optimized 3D T2WI significantly improved image quality, supporting its clinical feasibility as a valuable adjunct to contrast-enhanced breast MRI for lesion characterization and morphological assessment.

Keywords: magnetic resonance imaging, phantom, optimization of the imaging parameters of 3D T2WI, comparison 3D T2WI with 2D T2WI, breast

This is an Open Access article distributed under the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License. To view the details of this license, please visit (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Received: December 15, 2025; Accepted: April 3, 2026

Corresponding Author: Kazushige Ichikawa, MS

Department of Radiological Technology, Nagoya University Hospital,

65 Tsurumai-cho, Showa-ku, Nagoya 466-8560, Japan

Tel: +81-52-744-2327, Fax: +81-52-744-2335, E-mail: ichikawa.kazushige.z9@f.mail.nagoya-u.ac.jp

INTRODUCTION

Breast magnetic resonance imaging (MRI) has become indispensable for the diagnosis, characterization, and management of breast cancer. While contrast-enhanced sequences play a significant role, there is increasing emphasis on non-contrast MRI sequences, particularly T2-weighted image (T2WI), for comprehensive breast lesion assessment. The growing importance of T2 signal characteristics and edema evaluation has highlighted the value of these non-contrast sequences in lesion characterization and assessment of surrounding tissues, contributing to improved diagnostic accuracy.¹

T2WI is well-established in clinical MRI and is recommended in breast MRI guidelines,^{2,3} making it a crucial component of breast MRI protocols. T2WI is valuable for depicting edema, necrosis, lymph nodes, and cysts⁴ and for providing additional information to help differentiate between benign and malignant lesions.^{5,6} Notably, T2WI hyperintensity descriptor has been newly added to the lexicon in the American College of Radiology (ACR) BI-RADS v2025 Manual.³ In preoperative MRI, accurately differentiating additionally detected enhancing lesions is crucial for optimal surgical planning. Previous studies evaluating breast MRI, including preoperative examinations, have reported the clinical utility of T2WI in conjunction with contrast-enhanced T1-weighted image (CE-T1WI) to improve the differentiation of these MRI-detected lesions and effectively reduce false positives.^{7,8} Furthermore, the high signal intensity (SI) from subcutaneous and prepectoral edema is an important finding, often indicating occult inflammatory breast cancer.⁹ Reports have also highlighted the implementation of T2 mapping as an indicator¹⁰ or predictor¹¹ of the response to preoperative chemotherapy, underscoring T2WI's potential in treatment monitoring.

T2WI can provide complementary information that improves lesion classification.^{1,12} However, while two-dimensional T2WI (2D T2WI) is currently the most widely used technique, it has limitations in thicker slice that can hinder the observation of small lesions. Three-dimensional T2WI (3D T2WI) has emerged as a potential solution to address these limitations. Several studies have compared the performance of 3D with 2D, in the breast^{13,14} and in the spinal cord,¹⁵ obstetrics and gynecology,¹⁶ and prostate.¹⁷

Other advantages of 3D T2WI are showing reduction in respiratory motion artifacts relative to 2D T2WI¹⁸ and free from magnetization transfer (MT) effects. Multi-slice 2D sequence is widely known to generate MT.¹⁹ The MT effect in a slice is dependent on the amount of off-resonance radiofrequency power irradiated per repetition time (TR) and leads to signal decreases. This phenomenon has been observed in breast MRI, where the MT ratio for malignant tumors was lower than that of benign tumors and a fibroglandular tissue (FGT).²⁰ Moreover, MT in multi-slice 2D sequences was reported to lead to the underestimation of T2 values.²¹ These factors may contribute to the superior image quality observed with 3D T2WI.

The refocusing flip angle (FA) type in 3D T2WI significantly contributes to T2 contrast, with the variable refocusing flip angle (VRFA) type demonstrating superior image quality compared to the constant FA for the brain²² and prostate.¹⁷ However, the optimal implementation of 3D T2WI with VRFA for breast has not been fully investigated.

The aims of this study are firstly to optimize 3D T2WI in a phantom study, achieving an equivalent scan time to 2D T2WI, and secondly to compare the image quality and diagnostic potential of the optimized 3D T2WI with 2D T2WI in clinical breast MRI.

MATERIALS AND METHODS

Phantom study

Contrast-to-noise ratio. An International Society of Magnetic Resonance in Medicine/National Institute of Standards and Technology (ISMRM/NIST) system phantom²³ (Fig. 1) was scanned to evaluate the contrast-to-noise ratio (CNR) of 2D T2WI and 3D T2WI. We scanned a T2 array segment which was filled with MnCl₂-doped water. The T2 values of the spheres were provided by the manufacturer.²⁴ Following previous studies, we assumed the T2-2, T2-6, T2-7, and T2-8 spheres as representing a cyst-mimicking sphere,²⁵ a benign tumor-mimicking sphere,²⁶ a malignant tumor-mimicking sphere,²⁶ and a breast FGT-mimicking sphere,²⁷ respectively. T1 and T2 values for the T2-2, T2-6, T2-7, and T2-8 spheres were 2173 and 403 millisecond (msec), 1044 and 96 msec, 801 and 64 msec, and 608 and 46 msec, respectively.

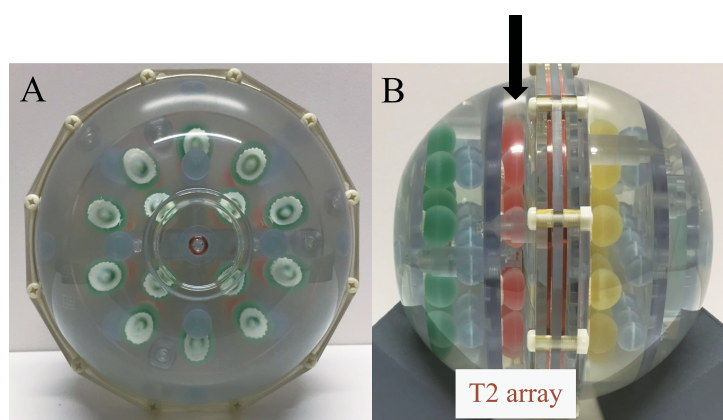


Fig. 1 An International Society of Magnetic Resonance in Medicine/National Institute of Standards and Technology (ISMRM/NIST) MRI system phantom

Fig. 1A: Frontal view

Fig. 1B: Lateral view

MRI indicates magnetic resonance imaging.

Resolution analysis. Additionally, the ISMRM/NIST phantom was also utilized for resolution analysis. The pin phantom was scanned, and pin diameters were 0.9 and 1.0 mm, respectively.

A visual assessment was performed to determine which imaging parameters exhibited the least blurring of the pin phantom.

MRI acquisition. Imaging was performed using an 18-channel phased-array surface coil on a 3T scanner (Prisma; Siemens Healthineers, Erlangen, Germany) once per examination. These coils were chosen due to the size limitations of the breast coil for the phantoms. The room temperature was maintained at 24.3 °C. 3D T2WI was acquired using sampling perfection with application optimized contrasts by using different flip angle evolution (SPACE) sequence.²⁸ We investigated the optimal imaging parameters for 3D T2WI by examining:

- CNR
 - A) Comparison of different refocusing FA types (3D with VRFA, 3D with constant FA)
 - B) Evaluation of varying equivalent echo times (TE) (80, 90, 100, 110, and 120 msec)
- Resolution analysis
 - C) Examination of varying acquired voxel sizes ($1.1 \times 0.8 \times 2.0 \text{ mm}^3$ for 2D and $1.0 \times 0.8 \times 1.4$, $0.8 \times 0.6 \times 1.4$, $0.7 \times 0.5 \times 1.4 \text{ mm}^3$ for 3D) and equivalent TE (100, 110, and 120 msec for 3D)

While optimizing 3D T2WI, we ensured that the acquisition time was equivalent to that of 2D T2WI. The number of slices and slice thickness were made equivalent to those in the CE T1WI. A summary of the imaging parameters of 2D T2WI and 3D T2WI is shown in Table 1.

In acquisition method C, as shown in Table 1, we varied the reduction factor obtained from the generalized autocalibrating partially parallel acquisitions (GRAPPA) technique to achieve the

Table 1 Summary of the imaging parameters of 2D T2WI and 3D T2WI in the phantom study

	2D T2WI	3D T2WI									
		A			B					C	
Field of view (mm ²)	350×200	350×200			350×200					350×200	
Acquired matrix size	314×256	420×320			420×320					336×256	420×320 504×384
TR (msec)	5480	2500 1500			2500					2500	
Equivalent TE (msec)	77	100	100	80	90	100	110	120	100	110	120
Data filling percentage	100	97	74	84	90	97	96	90	97	96	90
Echo space (msec)	9.6	3.4			3.4					3.3	3.4 3.6
Echo train length	11	160 97			160					160	
Refocusing flip angle type	Constant	Variable	Constant			Variable					Variable
Flip angle (degree)	120	N/A ^b 120			N/A ^b					N/A ^b	
Reduction factor ^a (phase×slice)	2×1	5×1			5×1					4×1	5×1 6×1
Fat suppression	SPAIR	SPAIR			SPAIR					SPAIR	
No. of slices	72	144			144					144	
Slice gap (mm)	0	N/A ^b			N/A ^b					N/A ^b	
Slice ordering	Interleave	N/A ^b			N/A ^b					N/A ^b	
Concatenations	2	N/A ^b			N/A ^b					N/A ^b	
Acquired voxel size (mm ³)	1.1×0.8×2.0	0.8×0.6×1.4			0.8×0.6×1.4					1.0×0.8×1.4	0.8×0.6×1.4 0.7×0.5×1.4
Reconstructed voxel size ^c (mm ³)	0.4×0.4×2.0	0.3×0.3×1.0			0.3×0.3×1.0					0.4×0.4×1.0	0.3×0.3×1.0 0.3×0.3×1.0
Acquisition time (sec)	219	218			218					218	

^a Obtained from generalized autocalibrating partially parallel acquisitions (GRAPPA) technique, ^b Not applicable,

^c Zero filled interpolation applied.

2D T2WI indicates two-dimensional T2-weighted image; 3D T2WI, three-dimensional T2-weighted image; TR, repetition time; TE, echo time; SPAIR, spectral attenuated inversion recovery.

We investigated the optimization of 3D T2WI parameters in terms of A, examining contrast-to-noise ratio (CNR) with different refocusing flip angle type; B, examining CNR varying equivalent TE; and C, resolution analysis varying acquired voxel size and equivalent TE.

same acquisition time. Both 2D and 3D sequences adopted spectral attenuated inversion recovery (commonly known as SPAIR) for fat suppression and applied signal uniformity correction (normalization filter) to compensate for spatial signal variations inherent to GRAPPA.

Quantitative analysis. Regions of interest (ROI) were manually placed on the four spheres in the T2 array segment on the MRI console. CNR was calculated from the SI and standard deviation (SD) obtained from ROI measurements as follows:

$$CNR = \frac{SI - SI_{FGT}}{\sqrt{\frac{(SD^2 + SD_{FGT}^2)}{2}}}.$$

Patient study

Patients. This retrospective study, approved by Nagoya University Hospital Institutional Review Board (approval no. 2023-0426), included 70 female patients (aged 28–75 years, median 49 years) with suspected or diagnosed breast cancer who underwent multiparametric breast MRI between August and December 2023. The informed consent was waived because our study was a retrospective type. An experienced breast radiologist (with 25 years of experience) reviewed the 70 MRI examinations and identified 62 enhanced mass lesions in 57 patients. These lesions were included in this study for quantitative and qualitative analyses. Other enhancing lesions, specifically non-mass enhancement and foci, were excluded from the analysis. Of the 62 mass lesions, 54 were pathologically confirmed as breast cancer. The breast cancer subtypes were as follows: invasive breast carcinoma of no special type (luminal, $n = 33$; human epidermal growth factor receptor 2 (HER2)-enriched, $n = 7$; triple-negative breast cancer [TNBC], $n = 11$), invasive lobular carcinoma ($n = 1$), and ductal carcinoma in situ ($n = 2$). The remaining eight lesions were incidentally detected coexisting lesions; four were pathologically confirmed as benign (unusual ductal hyperplasia, $n = 1$; intraductal papilloma, $n = 2$; fibroadenoma, $n = 1$), and four were considered highly likely to be benign on imaging findings and demonstrated no evidence of malignancy during subsequent follow-up.

MRI acquisition. MRI was performed using an 18-channel breast coil on the 3T scanner. Our multiparametric sequences included fat-suppressed 2D T2WI, fat-suppressed optimized 3D T2WI, and CE T1WI (Table 2).

Table 2 Summary of the imaging parameters of 2D T2WI and 3D T2WI in the patient study

	CE T1WI	2D T2WI	3D T2WI
Field of view (mm ²)	350×200	350×200	350×200
Acquired matrix size	323×288	314×256	420×320
TR (msec)	4.9	5480	2500
Equivalent TE (msec)	1.6	77	100
Echo space (msec)	4.9	9.6	3.4
Echo train length	N/A ^b	11	160
Refocusing flip angle type	N/A ^b	Constant	Variable
Flip angle (degree)	11	120	N/A ^b
Reduction factor ^a (phase×slice)	3×1	2×1	5×1
Fat suppression	SPAIR	SPAIR	SPAIR
No. of slices	144	72	144

Slice gap (mm)	N/A ^b	0	N/A ^b
Slice ordering	N/A ^b	Interleave	N/A ^b
Concatenations	N/A ^b	2	N/A ^b
Acquired voxel size (mm ³)	1.0×0.6×1.7	1.1×0.8×2.0	0.8×0.6×1.4
Reconstructed voxel size ^c (mm ³)	0.3×0.3×1.0	0.4×0.4×2.0	0.3×0.3×1.0
Acquisition time (sec)	70	219	218

^a Obtained from generalized autocalibrating partially parallel acquisitions (GRAPPA) technique,

^b Not applicable, ^c Zero filled interpolation applied.

CE T1WI indicates contrast-enhanced T1-weighted image; 2D T2WI, two-dimensional T2-weighted image; 3D T2WI, three-dimensional T2-weighted image; TR, repetition time; TE, echo time; SPAIR, spectral attenuated inversion recovery.

Quantitative analysis. ROIs of lesions were determined on the MRI console by automatically extracting the contour of the contrast-enhanced mass on CE T1WI and copying it to the T2WI. Furthermore, ROIs of FGT were determined by automatic extraction on T1-weighted non-fat-suppressed images.

Signal-to-noise ratio (SNR) and CNR were calculated from the SI obtained from ROI measurements as follows:

$$SNR = \frac{SI}{SD},$$

$$CNR = \frac{SI_{lesion} - SI_{FGT}}{\sqrt{\frac{(SD_{lesion}^2 + SD_{FGT}^2)}{2}}},$$

where SI and SD represent the mean signal intensity and standard deviation within the ROI, respectively.

Qualitative analysis. The 2D T2WI, 3D T2WI, and CE T1WI of the 70 patients were transferred to the image viewer workstation (syngo.via; Siemens Healthcare, Erlangen, Germany). Before the review, the images were de-identified and randomly arranged. The experienced breast radiologist (with 25 years of experience) identified 62 mass lesions in 57 patients using CE T1WI and recorded their locations. The other two experienced breast radiologists (with 15 and 20 years of experience, respectively) independently evaluated all axial T2WI using a 5-point Likert scale (1 = non-diagnostic level, 2 = poor, 3 = moderate, 4 = good, 5 = excellent) for image quality parameters. And these analyses were performed with readers blinded to whether the images were acquired with 2D T2WI or 3D T2WI. In all 70 cases, they assessed structural details, overall image quality, and artifacts of the entire image. For the 62 mass lesions, while being provided with information on their recorded locations, they additionally evaluated lesion conspicuity or morphology contrast and internal characteristics. Structural details were interpreted as the clarity in depicting the internal structures of FGT, including cysts, and the anatomical structures such as skin and chest wall. Lesion conspicuity or morphology contrast describes the contrast between the mass and the surrounding background tissue. The lesions' internal characteristics were defined as the ability to evaluate the internal heterogeneity of the mass. The mean and standard error of the scores were calculated for each parameter.

Furthermore, in the 62 mass lesions, the radiologists evaluated the presence of intratumoral necrosis (1 = no necrosis, 2 = presence of necrosis) and assigned a breast edema score (1 = no edema, 2 = peritumoral edema, 3 = prepectoral edema, 4 = subcutaneous edema).

Statistical analysis. The Wilcoxon signed-rank test was used to examine the statistical significance of differences between 2D T2WI and 3D T2WI for quantitative and qualitative measures in the patient study. Specifically, this test was applied to compare SNR and CNR, and image quality scores for lesion conspicuity or morphology contrast, internal characteristics, structural details, overall image quality, and artifact presence.

To assess the 2D T2WI-3D T2WI agreement, we used the κ -coefficient to evaluate their concordance in identifying the presence of intratumoral necrosis and assigning breast edema scores. Furthermore, to evaluate inter-reader agreement, weighted Cohen's κ -coefficients were calculated for lesion conspicuity or morphology contrast, internal characteristics, structural details, overall image quality, and artifact presence. $P < 0.05$ was considered statistically significant for all tests. All statistical analyses were performed using R software (version 4.3.3; R Foundation for Statistical Computing, Vienna, Austria).

RESULTS

Phantom study

Our investigation of optimal 3D T2WI imaging parameters yielded several important findings, as summarized in Table 3.

- CNR

A) Varying refocusing FA types

The 3D T2WI with VRFA consistently provided higher CNR across all spheres compared to 3D with constant FA, however, lower than 2D T2WI as shown in Table 3.

B) Varying equivalent TE

CNR between the malignant tumor-mimicking sphere and FGT-mimicking sphere, and the between benign tumor-mimicking sphere and FGT-mimicking sphere was highest at equivalent TE

Table 3 Summary of the CNR

			CNR							
			2D T2WI	3D T2WI						
				A		B				
T2 sphere	Ref. T1 value	Ref. T2 value		Variable FA	Constant FA	TE 80	TE 90	TE 100	TE 110	TE 120
T2-2	2173	403	83.5	31.5	13.4	20.5	24.5	31.5	30.2	38.1
T2-6	1044	96	37.2	18.1	8.8	10.6	12.9	18.1	17.3	17.2
T2-7	801	64	22.5	9.1	4.5	5.4	6.5	9.1	8.2	7.8
T2-8	608	46	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

CNR indicates contrast-to-noise ratio; 2D T2WI, two-dimensional T2-weighted image; 3D T2WI, three-dimensional T2-weighted image; TE, echo time; FA, flip angle.

T2-2, T2-6, T2-7, and T2-8 spheres represent a cyst-mimicking sphere, a benign tumor-mimicking sphere, a malignant tumor-mimicking sphere, and a fibroglandular tissue-mimicking sphere, respectively. A, examining CNR with different refocusing flip angle type; B, examining CNR varying equivalent TEs.

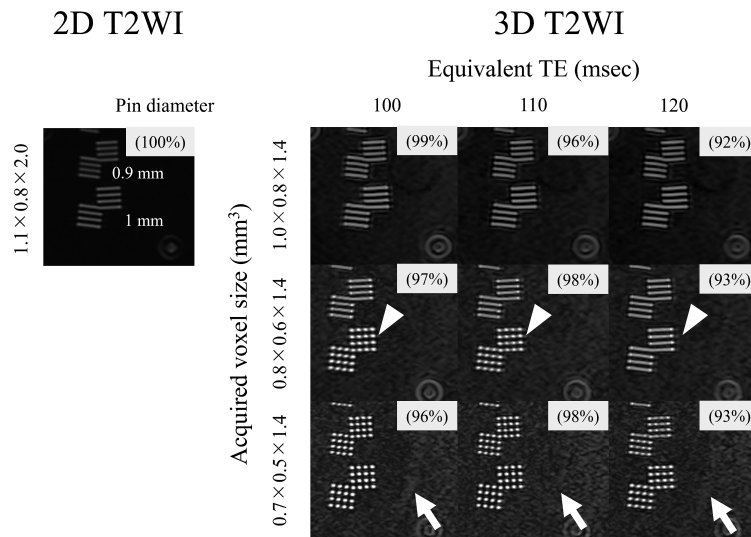


Fig. 2 Resolution analysis varying acquired voxel size and equivalent TE

The number in parentheses shows data filling percentages in the phase direction. These ratios depended on TE when compared in the same acquired voxel size. We could confirm that the larger these ratios were, the less the blur was (arrowheads). When scanned with an acquired voxel size of $0.7 \times 0.5 \times 1.4$ mm³, unfolding errors in parallel imaging were found (arrows) because of too high reduction factor of 6. Consequently, we concluded that the optimal acquired voxel size and equivalent TE were $0.8 \times 0.6 \times 1.4$ mm³ and 100 msec, respectively. 2D T2WI indicates two-dimensional T2-weighted image; 3D T2WI, three-dimensional T2-weighted image; TE, echo time.

of 100 msec for 3D T2WI, whereas CNR between the cyst-mimicking sphere and FGT-mimicking sphere was highest at an equivalent TE of 120 msec. Since our study focuses on tumor contrast rather than cyst depiction, an equivalent TE of 100 msec was determined as the optimal TE.

- Resolution analysis

C) Varying acquired voxel size and equivalent TE

Results are shown in Fig. 2. The data filling percentages in the phase direction, shown in parentheses, were dependent on TE when compared at the same acquired voxel size. Higher percentages corresponded to reduced blur, as indicated by arrowheads in Fig. 2. When scanned with an acquired voxel size of $0.7 \times 0.5 \times 1.4$ mm³, unfolding errors in parallel imaging were found (arrows) due to a high reduction factor of 6.

Consequently, we concluded that the optimal balance between resolution and image quality was achieved with an acquired voxel size of $0.8 \times 0.6 \times 1.4$ mm³ and an equivalent TE of 100 msec.

Patient study

Quantitative analysis. The SNR of lesions obtained from 2D T2WI and 3D T2WI were 6.23 ± 2.83 and 5.96 ± 2.84 ($p > 0.05$), respectively. For FGT, SNR obtained from 2D T2WI and 3D T2WI were 6.59 ± 3.00 and 6.33 ± 3.38 ($p > 0.05$), respectively. Notably, the CNR in 3D T2WI was significantly higher than in 2D T2WI (3.62 ± 2.74 vs. 4.15 ± 3.11 , $p < 0.05$).

Qualitative analysis. Example images obtained by 2D T2WI and 3D T2WI are presented in Fig. 3. These images were obtained from a 36-year-old female with luminal-type invasive ductal carcinoma of the left breast, stage IIB (T2N1M0) (Fig. 3A) and a 61-year-old female with TNBC of the right breast, stage IIIC (T2N3M0) (Fig. 3B). Compared to 2D T2WI, 3D T2WI demonstrated superior ability to delineate peritumoral edema and lesion morphology (Fig.

3A) as well as morphology contrast and internal characteristics (Fig. 3B).

3D T2WI demonstrated a reduction in respiratory motion artifacts relative to 2D T2WI (Fig. 4). This finding is consistent with previous studies in other anatomical regions.¹⁸

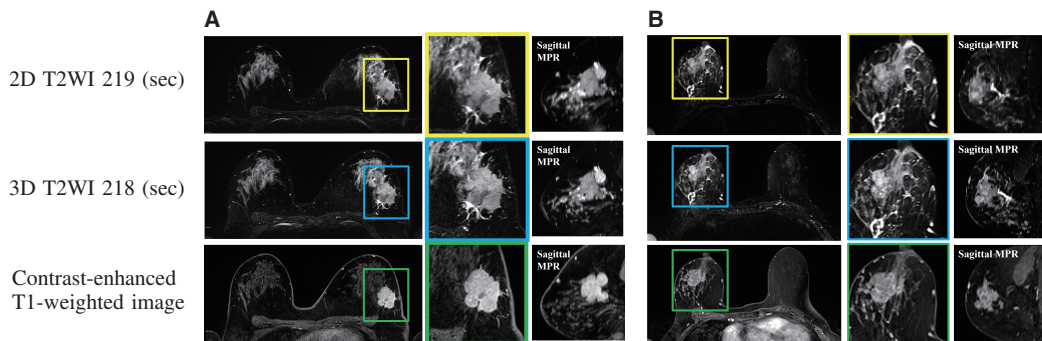


Fig. 3 Example images obtained by 2D T2WI and 3D T2WI

Fig. 3A: A 36-year-old female with luminal type invasive ductal carcinoma of the left breast, stage IIB (T2N1M0). Peritumoral edema and lesion morphology were more clearly delineated on 3D T2WI compared to 2D T2WI.

Fig. 3B: A 61-year-old female with triple-negative cancer of the right breast, stage IIIC (T2N3M0). Morphology contrast and internal characteristics were more clearly delineated on 3D T2WI compared to 2D T2WI. 2D T2WI indicates two-dimensional T2-weighted image; 3D T2WI, three-dimensional T2-weighted image; MPR, multi planar reconstruction.

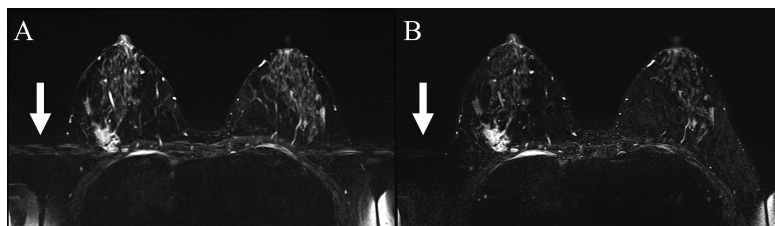


Fig. 4 Example images showing the difference of respiratory artifact between 2D T2WI and 3D T2WI

Fig. 4A: 2D T2WI

Fig. 4B: 3D T2WI

3D T2WI shows less respiratory artifact than 2D T2WI. 2D T2WI indicates two-dimensional T2-weighted image; 3D T2WI, three-dimensional T2-weighted image.

A summary of the Likert scores is shown in Table 4. 3D T2WI showed significantly higher scores across all evaluation criteria compared to 2D T2WI ($p < 0.01$). The inter-reader agreement for lesion conspicuity, morphology contrast, internal characteristics, structural details, and overall image quality was fair, with κ values of 0.28, 0.33, 0.34, and 0.31, respectively. The inter-reader agreement for the presence of artifacts was slight, with a κ value of 0.14.

Table 5 and Table 6 summarize the Likert scores for lesion conspicuity or morphology contrast and lesion internal characteristics according to histologic type and breast cancer subtype. Across all categories, 3D T2WI showed higher scores than 2D T2WI. The presence of intratumoral necrosis and breast edema was found to be consistent between 2D and 3D T2WI in all cases. However, edema tended to be more clearly delineated in 3D T2WI (Fig. 3A). Agreement between 2D T2WI and 3D T2WI for the presence of intratumoral necrosis and breast edema scores was perfect (κ -coefficient = 1.0).

Table 4 Summary of the Likert scores

	Lesion conspicuity or morphology contrast			Lesion internal characteristics			Structural details			Overall image quality			Artifacts		
	2D T2WI	3D T2WI	2D T2WI	3D T2WI	2D T2WI	3D T2WI	2D T2WI	3D T2WI	2D T2WI	3D T2WI	2D T2WI	3D T2WI	2D T2WI	3D T2WI	2D T2WI
Reader 1	3.7±0.1	4.7±0.1	3.7±0.1	4.7±0.1	4.7±0.1	4.7±0.1	3.7±0.1	4.8±0.0	3.6±0.1	4.7±0.1	4.1±0.1	4.6±0.1	4.1±0.1	4.6±0.1	4.1±0.1
Reader 2	4.0±0.6	4.6±0.6	4.0±0.6	4.6±0.6	4.6±0.5	4.6±0.5	4.2±0.5	4.8±0.4	4.1±0.6	4.7±0.5	3.2±0.6	4.1±0.5	3.2±0.6	4.1±0.5	3.2±0.6
Data are presented as mean ± standard error.															
2D T2WI, two-dimensional T2-weighted image; 3D T2WI, three-dimensional T2-weighted image.															
3D T2WI showed significantly higher scores in all evaluation criteria compared to 2D T2WI (<i>p</i> < 0.01).															

Table 5 Summary of the Likert scores for lesion conspicuity or morphology contrast according to histologic type and breast cancer subtype

	Lesion conspicuity or morphology contrast												Benign lesions (n = 8)		
	Breast cancer (n = 54)														
	Invasive breast carcinoma of no special type						Invasive lobular carcinoma (n = 1)			Ductal carcinoma in situ (n = 2)					
	Luminal (n = 33)		Her2 (n = 7)		Triple-negative breast cancer (n = 11)		2D T2WI	3D T2WI	2D T2WI	3D T2WI	2D T2WI	3D T2WI			
Reader 1	3.6±0.1	4.6±0.1	3.9±0.3	5.0±0.0	3.5±0.2	5.0±0.0	4.0±0.0	5.0±0.0	3.5±0.4	4.5±0.4	4.3±0.2	4.5±0.3			
Reader 2	4.1±0.1	4.6±0.1	3.9±0.2	4.7±0.2	4.2±0.2	4.8±0.1	3.0±0.0	4.0±0.0	4.0±0.7	4.5±0.4	4.0±0.3	4.1±0.3			
Data are presented as mean ± standard error.															
2D T2WI indicates two-dimensional T2-weighted image; 3D T2WI, three-dimensional T2-weighted image; Her2, human epidermal growth factor receptor 2.															

Table 6 Summary of the Likert scores for lesion internal characteristics according to histologic type and breast cancer subtype

	Lesion internal characteristics														Benign lesions (n = 8)		
	Breast cancer (n = 54)																
	Invasive breast carcinoma of no special type						Invasive lobular carcinoma (n = 1)			Ductal carcinoma in situ (n = 2)							
	Luminal (n = 33)		Her2 (n = 7)		Triple-negative breast cancer (n = 11)		2D T2WI	3D T2WI	2D T2WI	3D T2WI	2D T2WI	3D T2WI	2D T2WI	3D T2WI			
Reader 1	3.7±0.1	4.6±0.1	3.7±0.2	4.7±0.3	3.5±0.2	4.9±0.1	3.0±0.0	5.0±0.0	4.0±0.0	5.0±0.0	4.1±0.1	4.9±0.1	4.0±0.0	4.1±0.1			
Reader 2	3.9±0.1	4.6±0.1	4.1±0.2	4.7±0.2	4.2±0.1	5.0±0.0	3.0±0.0	4.0±0.0	4.0±0.0	5.0±0.0	3.8±0.2	4.1±0.3	4.0±0.0	4.1±0.3			
Data are presented as mean ± standard error.																	
2D T2WI indicates two-dimensional T2-weighted image; 3D T2WI, three-dimensional T2-weighted image; Her2, human epidermal growth factor receptor 2.																	

DISCUSSION

This study aimed to optimize 3D T2WI parameters for breast MRI through phantom experiments and to evaluate its efficacy in clinical settings. Our findings demonstrate the potential of optimized 3D T2WI to enhance image quality and T2 signal intensity evaluation while maintaining comparable scan times to conventional 2D T2WI.

In the phantom study, we first examined which refocusing FA type could offer higher CNR between VRFA and constant FA. Our results showed that 3D T2WI with VRFA could provide higher CNR, enabling better tissue differentiation based on T2 signal characteristics. This finding aligns with previous studies.¹⁷ The superiority of VRFA can be attributed to its additional benefits, including reduced specific absorption rate (SAR)²⁸ and improved fat suppression.²² Busse et al demonstrated that tissue with shorter T1 and T2 values, such as fat, exhibits lower actual SI with VRFA, potentially reducing the visibility of fat suppression failures compared to constant FA.²²

CNR between the malignant tumor-mimicking sphere and FGT-mimicking sphere, and the between benign tumor-mimicking sphere and FGT-mimicking sphere was highest at equivalent TE of 100 msec for 3D T2WI, whereas CNR between the cyst-mimicking sphere and FGT-mimicking sphere was highest at an equivalent TE of 120 msec. The T2 value of the cyst-mimicking sphere was considerably longer than that of the other spheres; therefore, adequate SI was maintained even at longer TE values, which likely contributed to the higher CNR observed.

3D T2WI with VRFA is designed to achieve a pseudo steady-state signal for tissues with the T1 and T2 values specified in the console.²⁸ In our study, the T1 and T2 values set in the console were 940 msec and 100 msec, respectively, which were the default values of the scanner. These values were most equivalent to a benign tumor-mimicking sphere. Therefore, if these values been optimized for a malignant tumor mimicking sphere, the clinical performance of 3D T2WI with VRFA could be further improved.

The T1 values of the benign tumor-mimicking sphere, malignant tumor-mimicking sphere, and FGT-mimicking sphere were smaller than those of patients^{27,29}; therefore, the effect of differences in TR between 2D T2WI and 3D T2WI on CNR was expected to be minimal.

Furthermore, our resolution analysis revealed that a smaller acquired voxel size could provide less blur of the pins, as expected (Fig. 2). Additionally, we found that the optimized data filling percentage in the phase direction is a significant key factor for reducing blur, which is crucial for accurate T2 signal intensity evaluation. These findings guided our parameter selection for the clinical study.

In the patient study, despite using a thinner slice thickness for 2D T2WI (2 mm) compared to previous studies (4 mm),¹⁴ 3D T2WI demonstrated superior image quality scores. Setting a thinner slice thickness provides lower SNR but is less sensitive to the partial volume effect. However, our study showed that SNR was slightly higher for 2D T2WI whereas CNR was significantly higher for 3D T2WI, consistent with previous studies.¹⁴ Despite adequate SNR in 2D T2WI, 3D T2WI showed superior image quality. This improvement can be attributed to our phantom-based optimization process. The improved CNR is particularly important for accurate T2 signal intensity evaluation in clinical practice, especially for subtle tissue changes and edema assessment. Generally, most hyperintense lesions on T2WI are considered benign. While breast cancers typically show iso- to hypointensity, mucinous carcinoma (although not included in our study cohort) characteristically demonstrates hyperintensity.³ Furthermore, previous reports on T2WI findings according to breast cancer subtypes indicate that TNBC tends to show hyperintensity due to necrosis and exhibit peritumoral edema.^{30,31} Although T2WI findings are presumed to vary reflecting these histological differences, our visual assessment demonstrated that the Likert scores for 3D T2WI were consistently higher than those for 2D T2WI across

all subtypes of breast cancer. Importantly, our optimized 3D T2WI technique does not rely on advanced technologies like artificial intelligence or compressed sensing,¹⁴ potentially facilitating broader clinical implementation and making it accessible to many facilities.

CNR of 3D T2WI with VRFA was lower than that of 2D T2WI in the phantom study, whereas it was higher in the patient study. This difference might be attributed to the MT effect, which was considered less significant in the T2 spheres than in patient tissues. The relatively high number of slice excitations (36 per TR) might lead to reduced T2 contrast in 2D acquisition. However, because imaging sequences for MT measurement are not part of routine protocols and MT ratio cannot be measured in our study, further investigation is required.

In our study, the menstrual cycle was not obtained. It can influence breast MRI findings; however, this effect has been described primarily in the context of background parenchymal enhancement on CE T1WI.³² As far as we know, no studies have demonstrated that differences in menstrual cycle phase affect findings on T2WI.

Our study has several limitations. The phantom was too big to fit into the breast coil, preventing assessment under the same conditions as in the clinical study. However, we could not confirm unfolding errors because the breast coil has a narrower spatial sensitivity profile and we used the same reduction factor of 5 that showed no unfolding errors in the phantom study. Another limitation is that no training session was conducted prior to the image scoring, which may explain the slight inter-reader agreement for artifact presence and fair agreement for the remaining categories. Although inter-reader agreement might have been improved by implementing a structured training session and by providing more detailed scoring criteria, the primary aim of this study was to compare 2D and 3D T2WI. In this context, both readers consistently showed significantly higher qualitative scores with 3D T2WI across all evaluation criteria. Therefore, we believe that our findings are consistent with the conclusions of this study.

CONCLUSION

This study demonstrated that the optimized 3D T2WI significantly improved image quality while maintaining the same scan times. Our findings strongly support the feasibility of high-resolution 3D T2WI for implementation in clinical settings, offering valuable information to complement contrast-enhanced MRI for breast cancer characterization.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

FUNDING/SUPPORT

The authors declare that no funding was received for this work.

REFERENCES

- 1 Mann RM, Cho N, Moy L. Breast MRI: State of the Art. *Radiology*. 2019;292(3):520–536. doi:10.1148/radiol.2019182947
- 2 Mann RM, Kuhl CK, Kinkel K, Boetes C. Breast MRI: guidelines from the European Society of Breast Imaging. *Eur Radiol*. 2008;18(7):1307–1318. doi:10.1007/s00330-008-0863-7

- 3 DeMartini WB, Strigel RM, Pinker K, et al. Magnetic Resonance Imaging. In: *ACR BI-RADS v2025 Manual*. VA American College of Radiology; 2025.
- 4 Westra C, Dialani V, Mehta TS, Eisenberg RL. Using T2-weighted sequences to more accurately characterize breast masses seen on MRI. *AJR Am J Roentgenol*. 2014;202(3):W183–W190. doi:10.2214/AJR.13.11266
- 5 Kuhl CK, Klaschik S, Mielcarek P, Gieseke J, Wardelmann E, Schild HH. Do T2-weighted pulse sequences help with the differential diagnosis of enhancing lesions in dynamic breast MRI?. *J Magn Reson Imaging*. 1999;9(2):187–196. doi:10.1002/(sici)1522-2586(199902)9:2<187::aid-jmri6>3.0.co;2-2
- 6 Malich A, Fischer DR, Wurdinger S, et al. Potential MRI interpretation model: differentiation of benign from malignant breast masses. *AJR Am J Roentgenol*. 2005;185(4):964–970. doi:10.2214/AJR.04.1073
- 7 Alikhassi A, Li X, Au F, et al. False-positive incidental lesions detected on contrast-enhanced breast MRI: clinical and imaging features. *Breast Cancer Res Treat*. 2023;198(2):321–334. doi:10.1007/s10549-023-06861-y
- 8 Arponen O, Masarwah A, Sutela A, et al. Incidentally detected enhancing lesions found in breast MRI: analysis of apparent diffusion coefficient and T2 signal intensity significantly improves specificity. *Eur Radiol*. 2016;26(12):4361–4370. doi:10.1007/s00330-016-4326-2
- 9 Uematsu T, Kasami M, Watanabe J. Can T2-weighted 3-T breast MRI predict clinically occult inflammatory breast cancer before pathological examination? A single-center experience. *Breast Cancer*. 2014;21(1):115–121. doi:10.1007/s12282-012-0425-3
- 10 Liu L, Yin B, Geng DY, Lu YP, Peng WJ. Changes of T2 Relaxation Time From Neoadjuvant Chemotherapy in Breast Cancer Lesions. *Iran J Radiol*. 2016;13(3):e24014. doi:10.5812/iranjradiol.24014
- 11 Tan PC, Pickles MD, Lowry M, Manton DJ, Turnbull LW. Lesion T(2) relaxation times and volumes predict the response of malignant breast lesions to neoadjuvant chemotherapy. *Magn Reson Imaging*. 2008;26(1):26–34. doi:10.1016/j.mri.2007.04.002
- 12 Yuen S, Monzawa S, Yanai S, et al. The association between MRI findings and breast cancer subtypes: focused on the combination patterns on diffusion-weighted and T2-weighted images. *Breast Cancer*. 2020;27(5):1029–1037. doi:10.1007/s12282-020-01105-z
- 13 Moran CJ, Hargreaves BA, Saranathan M, et al. 3D T2-weighted spin echo imaging in the breast. *J Magn Reson Imaging*. 2014;39(2):332–338. doi:10.1002/jmri.24151
- 14 Yang F, Pan X, Zhu K, et al. Accelerated 3D high-resolution T2-weighted breast MRI with deep learning constrained compressed sensing, comparison with conventional T2-weighted sequence on 3.0 T. *Eur J Radiol*. 2022;156:110562. doi:10.1016/j.ejrad.2022.110562
- 15 Chokshi FH, Sadigh G, Carpenter W, Allen JW. Diagnostic Quality of 3D T2-SPACE Compared with T2-FSE in the Evaluation of Cervical Spine MRI Anatomy. *AJNR Am J Neuroradiol*. 2017;38(4):846–850. doi:10.3174/ajnr.A5080
- 16 Hecht EM, Yitta S, Lim RP, et al. Preliminary clinical experience at 3 T with a 3D T2-weighted sequence compared with multiplanar 2D for evaluation of the female pelvis. *AJR Am J Roentgenol*. 2011;197(2):W346–W352. doi:10.2214/AJR.10.5914
- 17 Tanaka U, Ueno Y, Morinaga Y, et al. Value of three-dimensional T2-weighted turbo spin-echo imaging with tissue-specific variable refocusing flip angle for 3-T magnetic resonance imaging of prostate cancer: comparison with conventional two- and three-dimensional T2-weighted turbo spin-echo imaging. *Jpn J Radiol*. 2017;35(12):707–717. doi:10.1007/s11604-017-0684-1
- 18 Barat M, Soyer P, Dautry R, et al. Preoperative detection of malignant liver tumors: Comparison of 3D-T2-weighted sequences with T2-weighted turbo spin-echo and single shot T2 at 1.5 T. *Eur J Radiol*. 2018;100:7–13. doi:10.1016/j.ejrad.2018.01.007
- 19 Santyr GE. Magnetization transfer effects in multislice MR imaging. *Magn Reson Imaging*. 1993;11(4):521–532. doi:10.1016/0730-725x(93)90471-o
- 20 Bonini RH, Zeotti D, Saraiva LA, et al. Magnetization transfer ratio as a predictor of malignancy in breast lesions: preliminary results. *Magn Reson Med*. 2008;59(5):1030–1034. doi:10.1002/mrm.21555
- 21 Radunsky D, Blumenfeld-Katzir T, Volovyk O, et al. Analysis of magnetization transfer (MT) influence on quantitative mapping of T2 relaxation time. *Magn Reson Med*. 2019;82(1):145–158. doi:10.1002/mrm.27704
- 22 Busse RF, Hariharan H, Vu A, Brittain JH. Fast spin echo sequences with very long echo trains: design of variable refocusing flip angle schedules and generation of clinical T2 contrast. *Magn Reson Med*. 2006;55(5):1030–1037. doi:10.1002/mrm.20863
- 23 Russek S, Boss M, Jackson E, et al. Characterization of NIST/ISMRM MRI system phantom. In: *Proceedings of the 20th Annual Meeting of ISMRM*. Melbourne, Australia; 2012.
- 24 Keenan KE, Stupic KF, Boss MA, et al. Comparison of T1 measurement using ISMRM/NIST system phantom. In: *Proceedings of the 24th Annual Meeting of ISMRM*. Singapore; 2016:3290.

- 25 McFarland EG, Mayo-Smith WW, Saini S, Hahn PF, Goldberg MA, Lee MJ. Hepatic hemangiomas and malignant tumors: improved differentiation with heavily T2-weighted conventional spin-echo MR imaging. *Radiology*. 1994;193(1):43–47. doi:10.1148/radiology.193.1.8090920
- 26 Merchant TE, Thelissen GR, de Graaf PW, Nieuwenhuizen CW, Kievit HC, Den Otter W. Application of a mixed imaging sequence for MR imaging characterization of human breast disease. *Acta Radiol*. 1993;34(4):356–361.
- 27 Rakow-Penner R, Daniel B, Yu H, Sawyer-Glover A, Glover GH. Relaxation times of breast tissue at 1.5T and 3T measured using IDEAL. *J Magn Reson Imaging*. 2006;23(1):87–91. doi:10.1002/jmri.20469
- 28 Mugler JP 3rd. Optimized three-dimensional fast-spin-echo MRI. *J Magn Reson Imaging*. 2014;39(4):745–767. doi:10.1002/jmri.24542
- 29 Meng L, Zhao X, Guo J, et al. Evaluation of the differentiation of benign and malignant breast lesions using synthetic relaxometry and the Kaiser score. *Front Oncol*. 2022;12:964078. doi:10.3389/fonc.2022.964078
- 30 Uematsu T, Kasami M, Yuen S. Triple-negative breast cancer: correlation between MR imaging and pathologic findings. *Radiology*. 2009;250(3):638–647. doi:10.1148/radiol.2503081054
- 31 Costantini M, Belli P, Distefano D, et al. Magnetic resonance imaging features in triple-negative breast cancer: comparison with luminal and HER2-overexpressing tumors. *Clin Breast Cancer*. 2012;12(5):331–339. doi:10.1016/j.clbc.2012.07.002
- 32 Kamitani T, Yabuuchi H, Kanemaki Y, et al. Effects of menstrual cycle on background parenchymal enhancement and detectability of breast cancer on dynamic contrast-enhanced breast MRI: A multicenter study of an Asian population. *Eur J Radiol*. 2019;110:130–135. doi:10.1016/j.ejrad.2018.11.025