Original Article | Breast Imaging

eISSN 2005-8330
https://doi.org/10.3348/kjr.2025.1382
Korean J Radiol 2026;27(4):305-317

Korean Journal of Radiology
KJR

Association of T2-Weighted Imaging Features in Invasive Breast Cancer With Clinicopathologic Features and Neoadjuvant Treatment Outcomes

Inyoung Youn[1], Yun Ho Roh[2], Min Jung Kim[3,4], Jung Hyun Yoon[3], Mi-ri Kwon[1], Vivian Youngjean Park[3]

[1]Department of Radiology, Kangbuk Samsung Hospital, Sungkyunkwan University School of Medicine, Seoul, Republic of Korea
[2]Biostatistics Collaboration Unit, Department of Biomedical Systems Informatics, Yonsei University College of Medicine, Seoul, Republic of Korea
[3]Department of Radiology, Research Institute of Radiological Science, Yonsei University College of Medicine, Seoul, Republic of Korea
[4]Department of Integrative Medicine Major in Digital Healthcare, Yonsei University College of Medicine, Seoul, Republic of Korea

Objective: To investigate the associations between T2-weighted imaging (T2WI) features and clinicopathologic characteristics in invasive breast cancer, as well as their relationship with treatment response to neoadjuvant chemotherapy (NAC).
Materials and Methods: This retrospective study included 179 women with invasive breast cancer who underwent preoperative 3T breast MRI between November 2020 and February 2021. Intratumoral T2 signal intensity (SI) and peritumoral edema were graded on T2WI, and T2 relaxation times were calculated both including and excluding necrotic or cystic areas. T2 relaxation times were compared across T2 SI grades using the Kruskal–Wallis test. Associations between T2 features and clinicopathologic factors were assessed using chi-square tests and logistic regression analyses. In patients who received NAC (n = 68), associations between T2 features and NAC outcomes were also evaluated.
Results: Higher intratumoral T2 SI and peritumoral edema grades were significantly associated with longer T2 relaxation times (P < 0.001). Intratumoral T2 SI grades were associated with higher clinical T category, axillary lymph node metastasis, and tumor multiplicity (all P < 0.05). Longer intratumoral T2 relaxation times were associated with higher clinical T category, hormone receptor (HR) negativity, and the triple-negative subtype (all P < 0.05), even after excluding necrotic or cystic areas. Higher peritumoral edema grades were associated with advanced clinical T category, HR negativity, and the triple-negative subtype (all P < 0.05). T2 relaxation times of peritumoral edema showed no significant associations, except with higher clinical T category (P = 0.005) and estrogen receptor status (P = 0.030). In the NAC subgroup, higher intratumoral T2 SI grades and longer T2 relaxation times were significantly associated with disease progression during NAC (P < 0.05), but not with non-pathologic complete response. Peritumoral edema showed no significant association with NAC outcomes (P > 0.05).
Conclusion: T2-weighted MRI features were associated with clinicopathologic factors, including clinical T category, HR status, triple-negative subtype, and disease progression during NAC.
Keywords: Breast cancer; Magnetic resonance imaging; Neoadjuvant therapy; T2 relaxation time; T2-weighted imaging

INTRODUCTION

Magnetic resonance imaging (MRI) is a powerful modality for evaluating breast cancer, providing both qualitative and quantitative information [1]. While early studies primarily focused on dynamic contrast-enhanced MRI [2-4], recent research has increasingly recognized the value of non-contrast sequences [1,5-9]. Although T2-weighted imaging (T2WI) is a standard sequence in breast MRI protocols, its role beyond improving diagnostic confidence in identifying probably benign lesions has been relatively underexplored [10]. Recently, T2WI features have been reported to be

Received: January 11, 2025 **Revised:** September 19, 2025 **Accepted:** January 2, 2026
Corresponding author: Vivian Youngjean Park, MD, PhD, Department of Radiology, Research Institute of Radiological Science, Yonsei University College of Medicine, 50-1 Yonsei-ro, Seodaemun-gu, Seoul 03722, Republic of Korea
• E-mail: VIVIANPARK0116@yuhs.ac

associated with patient outcomes and have contributed to multiparametric models, underscoring the need for further research on this sequence [7,11].

Visual assessments of T2WI, such as T2 hyperintensity and peritumoral edema, have been linked to prognostic factors—including tumor size, grade, lymph node metastasis, and recurrence—yet the assessment criteria vary among studies, ranging from binary water-signal comparisons to three-grade or edema location–based classifications [7,12-15]. T2 relaxation time, a quantitative parameter derived from T2WI that reflects tissue composition and microstructure, has shown promise in differentiating breast lesions [8,16]. Previous studies have suggested that T2 relaxation times differ between malignant and benign tumors and may change with neoadjuvant chemotherapy (NAC); however, data on their application in breast cancer remain limited [12,13,16].

There is a need to further investigate the role of T2WI features in breast cancer, particularly their associations with clinical, imaging, and pathological factors, as well as the potential significance of T2 relaxation times. This study aims to investigate the associations between T2WI features and clinicopathologic characteristics in invasive breast cancer and, among patients who received NAC, their relationship with treatment response.

MATERIALS AND METHODS

Study Sample

This single-center retrospective study was approved by the Institutional Review Board of Severance Hospital (IRB No. 4-2022-1425), and the requirement for written informed consent was waived. Consecutive women with newly diagnosed invasive breast cancer who underwent preoperative breast MRI using a 3T scanner between November 2020 and February 2021 were retrospectively identified.

Of the 256 women initially identified, 77 were excluded (Fig. 1): those who underwent MRI after excisional or vacuum-assisted biopsy (n = 12), did not undergo definitive surgery at our institution (treated elsewhere, n = 22), had mucinous carcinoma (n = 8), had distant metastasis at diagnosis (n = 1), had a history of previous breast cancer (n = 20), or had cancers that could not be evaluated on T2 mapping (n = 14). Only the index cancer was included for patients with multifocal/multicentric cancers. Mucinous carcinomas were excluded because their mucin-related high T2 signal intensity (SI) could confound associations with histopathologic features. Finally, 179 women (mean age, 52.7 ± 11.1 years) with 179 invasive breast cancers were included.

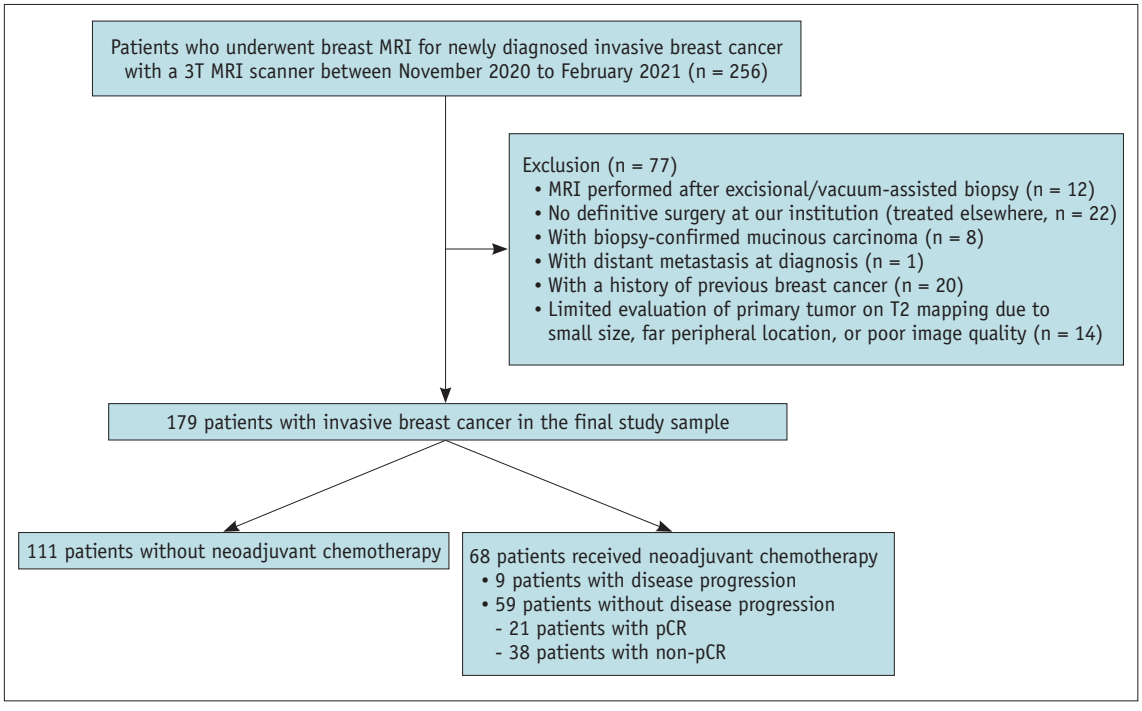

Fig. 1. Flowchart illustrating study sample selection. pCR = pathologic complete response

https://doi.org/10.3348/kjr.2025.1382

Korean Journal of Radiology
KJR

MRI Technique

Breast MRI examinations were performed on a 3T MRI system using the following protocol: a three-plane localizing sequence; a T2 mapping sequence for the quantification of T2 relaxation time using an axial multislice multiecho turbo spin-echo sequence (repetition time [TR], 2,532 ms; field of view, 400 x 400 mm^2; matrix, 320 x 320; section thickness, 3 mm; section gap, 2 mm; and 10 echo times [TEs] ranging

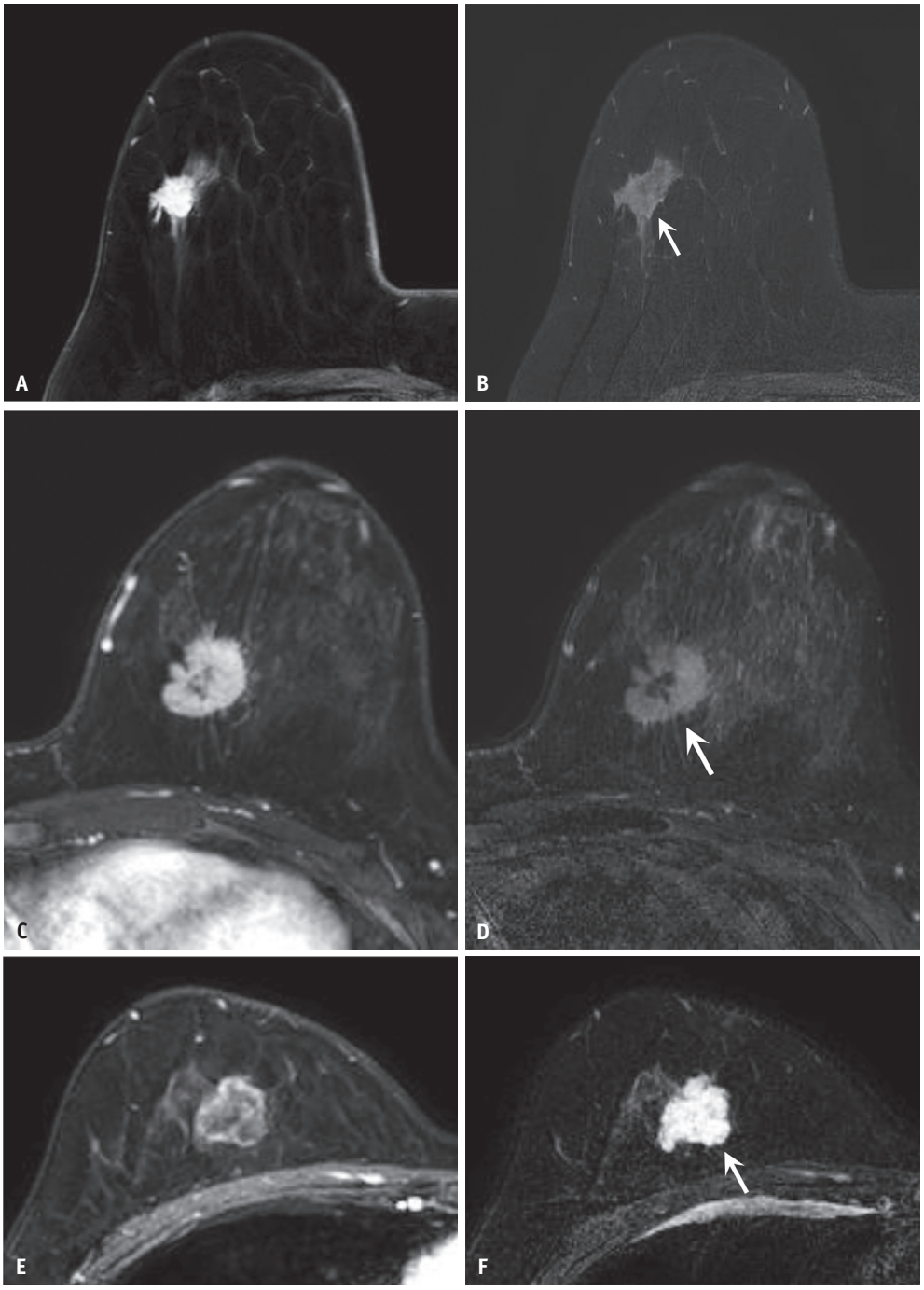

Fig. 2. Examples of intratumoral T2 signal intensity grades. **A, B:** Fat-suppressed T1-weighted early contrast-enhanced **(A)** and T2-weighted axial breast MR **(B)** images show intratumoral T2 signal intensity (arrow) lower than or equal to that of the surrounding breast tissue (grade 0). **C, D:** Fat-suppressed T1-weighted early contrast-enhanced **(C)** and T2-weighted axial breast MR **(D)** images show moderately high intratumoral T2 signal intensity (arrow), which remains lower than that of water (grade 1). **E, F:** Fat-suppressed T1-weighted early contrast-enhanced **(E)** and T2-weighted axial breast MR **(F)** images show intratumoral T2 signal intensity (arrow) as high as that of water (grade 2).

https://doi.org/10.3348/kjr.2025.1382

from 15 to 150 ms); an axial T2-weighted mDIXON sequence (mDIXON; TR/TE, 3,000–6,000/80 ms; matrix, 512 x 512; field of view, 250 x 320 mm^2; section thickness, 3 mm; no intersection gap); an axial diffusion-weighted sequence; an axial T1-weighted dynamic contrast-enhanced sequence with one precontrast and six postcontrast acquisitions; and an additional sagittal T1-weighted delayed postcontrast sequence. Further details on the MRI protocol are provided in the Supplementary Text 1.

T2WI Feature Grading and T2 Relaxation Time Measurement

Two breast radiologists (V.Y.P. and I.Y., with 10 and 12 years of experience in breast imaging, respectively) who were aware of tumor location but blinded to clinicopathologic information independently graded intratumoral T2 SI and peritumoral edema on fat-suppressed T2-weighted images. For patients who received NAC, the assessment was based on baseline breast MRI. Intratumoral T2 SI was graded from 0 to 2 relative to surrounding breast tissue: grade 0, tumor exhibiting SI lower than or equivalent to that of surrounding breast tissue; grade 1, focal or entire tumor exhibiting moderately high SI but lower than that of water; and grade 2, focal or entire tumor exhibiting high SI equivalent to that of water (Fig. 2). Peritumoral edema was graded from 0 to 2 based on the degree of SI surrounding the tumor on T2WI as follows: grade 0, absence of high SI; grade 1, moderately high SI but lower than that of water; and grade 2, SI equivalent to that of water (Fig. 3) [7]. Discordant cases were jointly reviewed by both radiologists and resolved by consensus.

For T2 relaxation time measurement, the tumor was manually segmented on two representative slices using commercial software (IntelliSpace Portal, Philips Healthcare, Best, Netherlands) by a radiologist with 10 years of subspecialty experience in breast imaging (V.Y.P.). Two approaches were applied: 1) including the entire tumor and 2) excluding definite necrotic or cystic areas. The first approach paralleled the method used for T2 SI grading by including necrotic or cystic regions, whereas the second approach excluded these areas to focus on the solid enhancing portion of the tumor. The mean T2 relaxation time was measured twice for each approach, and the average value was used for analysis. In cases showing peritumoral edema, the edematous region was also manually segmented twice on representative slices, and the average of the two mean T2 relaxation times was used (Fig. 4).

Data Collection

Clinicopathologic data were obtained from electronic medical records and included the following variables: patient age, tumor histology, clinical T category, tumor multiplicity within the ipsilateral breast, axillary lymph node metastasis, estrogen receptor (ER), progesterone receptor (PR), and human epidermal growth factor receptor 2 (HER2) status, as well as receipt of NAC. Tumors were classified into immunohistochemical subtypes—hormone receptor (HR; ER or PR)-positive/HER2-negative, HR-positive/HER2-positive, HR-negative/HER2-positive, and triple-negative breast cancer (TNBC)—and further grouped as TNBC vs. non-TNBC.

For patients who received NAC, breast MRI and mammography were routinely performed before treatment, during mid-treatment, and after completion of NAC prior to surgery, whereas breast ultrasound was performed before and after NAC. Additional imaging was conducted if clinical suspicion of disease progression arose. NAC response was evaluated according to two criteria: 1) progression vs. non-progression, and 2) non–pathologic complete response (non-pCR) vs. pCR. Disease progression was defined according to the Response Evaluation Criteria in Solid Tumors (RECIST) version 1.1 as a more than 20% increase in tumor size relative to the smallest prior measurement (nadir), with an absolute increase of at least 5 mm on MRI, or the appearance of new lesions during NAC [17]. pCR was defined as the absence of residual invasive carcinoma in the completely resected breast specimen and all sampled regional lymph nodes [18].

Statistical Analysis

Data were summarized as mean ± standard deviation for continuous variables and as frequencies and percentages for categorical variables. Consensus grades determined by the two radiologists were used for analysis, and interobserver variability was assessed using weighted kappa statistics. Interreader agreement was classified as follows: slight, 0.00–0.20; fair, 0.21–0.40; moderate, 0.41–0.60; substantial, 0.61–0.80; and almost perfect, 0.81–1.00 [19].

To evaluate the associations between T2WI feature grades and T2 relaxation times, mean T2 relaxation times were compared across grades of intratumoral T2 SI and peritumoral edema using the Kruskal–Wallis test. Clinicopathologic characteristics were compared according to intratumoral T2 SI and peritumoral edema grades using the chi-square test. Associations between T2 relaxation

https://doi.org/10.3348/kjr.2025.1382

Korean Journal of Radiology
KJR

times and clinicopathologic variables were analyzed using univariable logistic regression, and odds ratio (OR) values were calculated for each 10-ms increase in T2 relaxation time. Among patients who received NAC, associations between neoadjuvant treatment outcomes (progression vs. non-progression, non-pCR vs. pCR) and clinicopathologic or T2 variables—including intratumoral T2 SI and peritumoral edema grades and T2 relaxation times—were evaluated

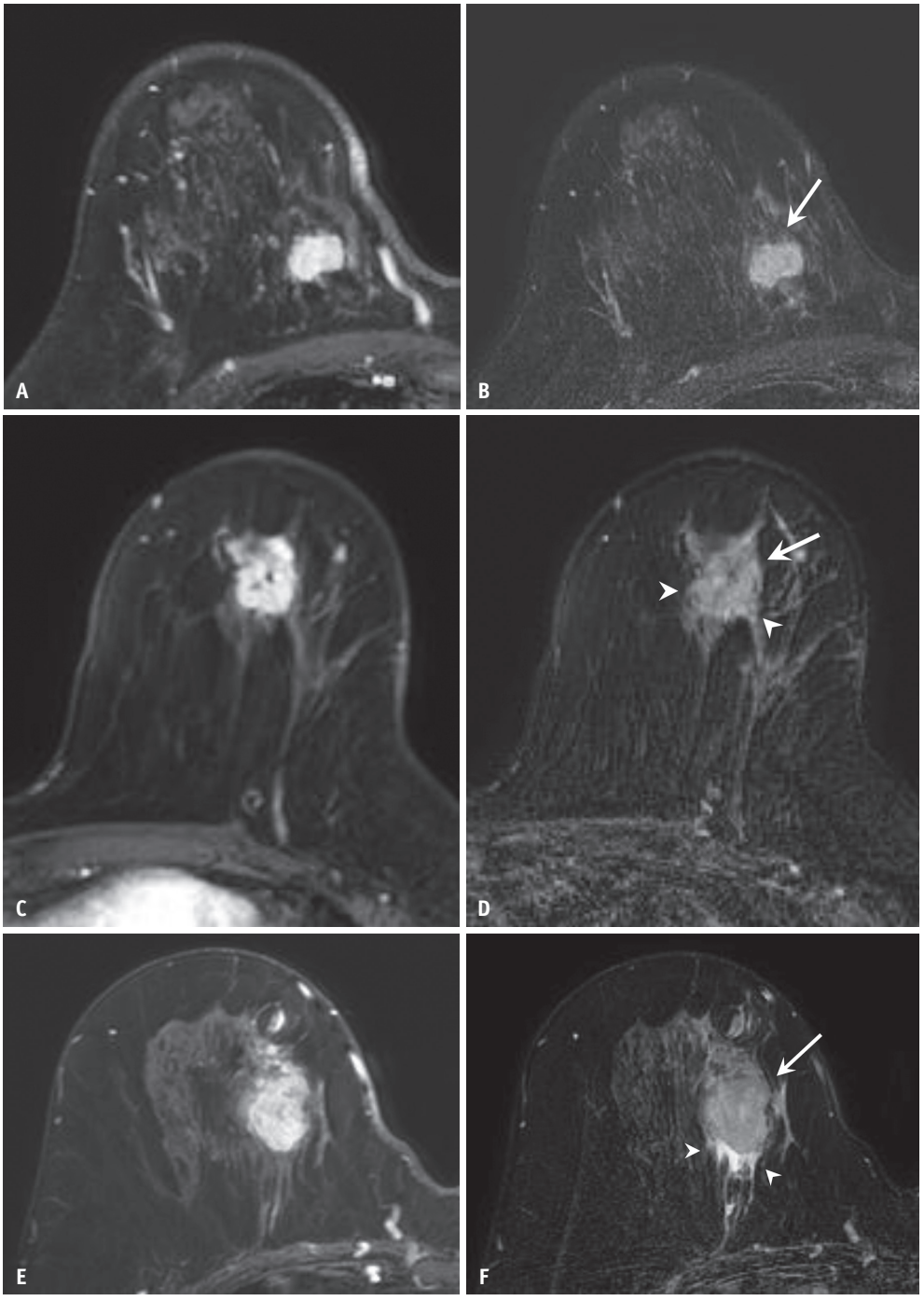

Fig. 3. Examples of peritumoral edema grades. **A, B:** Fat-suppressed T1-weighted early contrast-enhanced **(A)** and T2-weighted axial breast MR **(B)** images show the absence of high T2 signal intensity surrounding the tumor (arrow) (grade 0). **C, D:** Fat-suppressed T1-weighted early contrast-enhanced **(C)** and T2-weighted axial breast MR **(D)** images show moderately high T2 signal intensity surrounding the tumor (arrow) on **(D)**, which is lower than that of water (arrowheads) (grade 1). **E, F:** Fat-suppressed T1-weighted early contrast-enhanced **(E)** and T2-weighted axial breast MR **(F)** images show T2 signal intensity surrounding the tumor (arrow) as high as that of water (arrowheads) (grade 2).

https://doi.org/10.3348/kjr.2025.1382

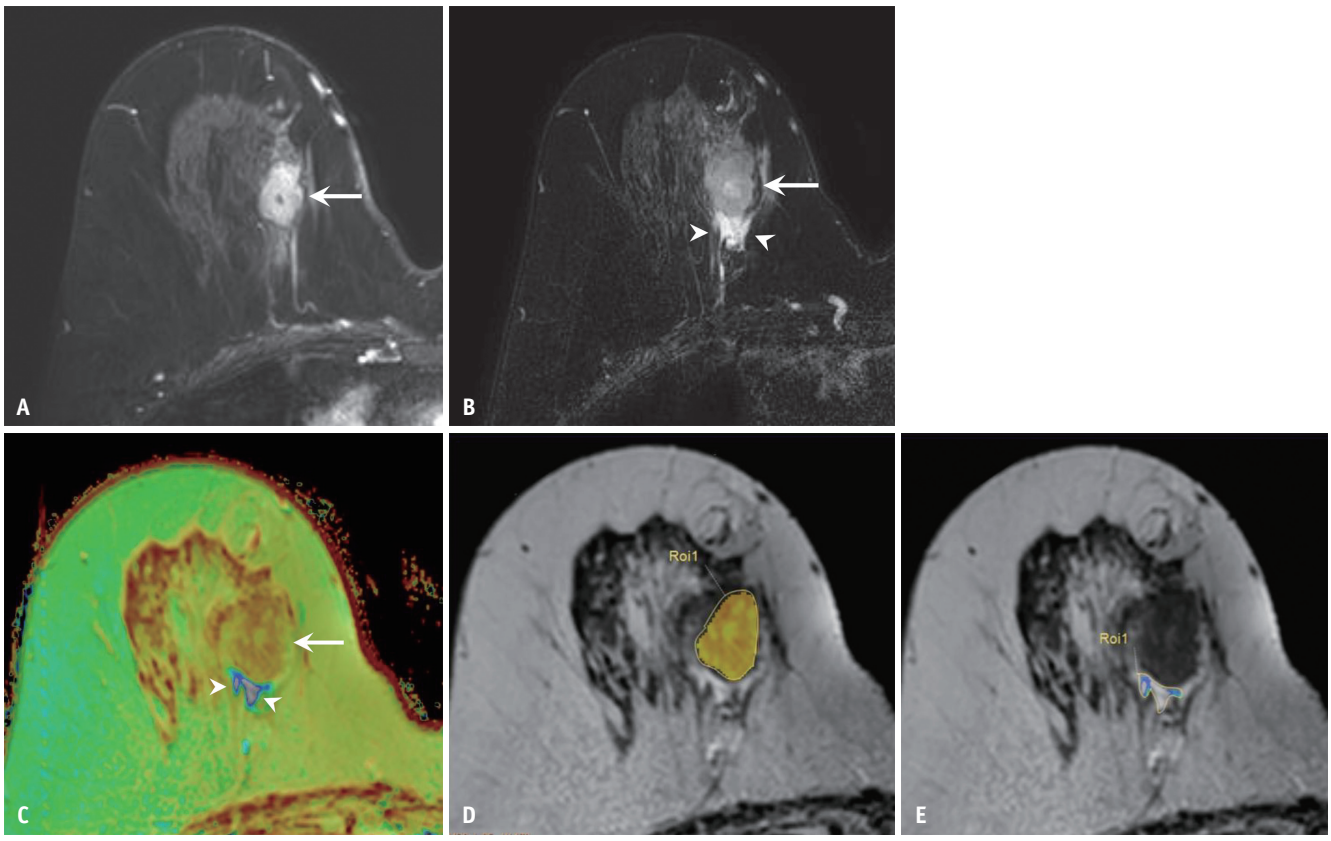

Fig. 4. T2 relaxation time mapping in a 54-year-old woman with triple-negative invasive ductal carcinoma that achieved pathologic complete response after neoadjuvant chemotherapy. **A:** Fat-suppressed T1-weighted early contrast-enhanced axial image shows a malignant mass in the right upper inner breast (arrow). **B:** On the fat-suppressed T2-weighted axial image, the mass (arrow) demonstrates grade 1 intratumoral T2 signal intensity and grade 2 peritumoral edema (arrowheads). **C:** The T2 color map shows the mass (arrow) and adjacent peritumoral edema (arrowheads). **D, E:** Manual segmentation of the tumor **(D)** and the peritumoral edema area **(E)** was performed twice, and the mean of the two measured T2 relaxation times was used for analysis.

using univariable logistic regression. Firth's penalized likelihood logistic regression was applied when the number of events was limited. All statistical analyses were performed using R software, version 4.2.2 (R Foundation for Statistical Computing, Vienna, Austria; http://www.R-project.org). Statistical significance was set at $P < 0.05$. For multiple comparisons across the three grades of intratumoral T2 SI and peritumoral edema, a Bonferroni-corrected threshold of $P < 0.017$ was applied, and adjusted *P*-values are reported.

RESULTS

Patient and Lesion Characteristics

Among the 179 invasive breast cancers included in the final cohort, 160 (89.4%) were invasive ductal carcinomas, 11 (6.1%) were invasive lobular carcinomas, and 8 (4.5%) were of other histologic types (Table 1). NAC was administered to 68 women (38.0%) before surgery. Additional clinicopathologic characteristics are summarized in Table 1.

Association Between T2WI Feature Grades and T2 Relaxation Time in Invasive Breast Cancers

The weighted kappa values for grading intratumoral T2 SI and peritumoral edema between reader 1 and reader 2 were 0.678 (95% confidence interval [CI], 0.564–0.792) and 0.771 (95% CI, 0.651–0.891), respectively, indicating substantial agreement. T2 relaxation times differed significantly across grades of intratumoral T2 SI and peritumoral edema (all $P < 0.05$; Supplementary Text 2, Supplementary Table 1).

Association Between Intratumoral T2 Assessment and Clinicopathologic Characteristics

Clinical T category distributions differed according to

https://doi.org/10.3348/kjr.2025.1382

Korean Journal of Radiology
KJR

intratumoral T2 SI grade (P = 0.016), with grade 2 lesions more frequently associated with clinical T2 tumors (48.4% for grade 0, 50.7% for grade 1, and 89.5% for grade 2; Table 2). Pairwise comparisons revealed significant differences between grade 0 and the other grades (grade 1, P = 0.012; grade 2, P = 0.027). The proportions of tumor multiplicity (P = 0.038) and axillary lymph node metastasis (P = 0.033) also varied according to intratumoral T2 SI grades; however, no subgroup differences remained significant after Bonferroni correction. No significant differences were observed in HR status, HER2 status, or TNBC subtype (all P > 0.05).

Table 1. Basic characteristics of 179 patients

Characteristics	Values
Age, yrs	52.7 ± 11.1
Tumor histology	
IDC	160 (89.4)
ILC	11 (6.1)
Others*	8 (4.5)
Clinical T category	
1	72 (40.2)
2	96 (53.6)
3	11 (6.1)
Multiplicity	
Yes	56 (31.3)
No	123 (68.7)
Axillary lymph node metastasis	
Yes	68 (38.0)
No	111 (62.0)
ER	
Positive	127 (70.9)
Negative	52 (29.1)
PR	
Positive	108 (60.3)
Negative	71 (39.7)
HER2	
Positive	33 (18.4)
Negative	146 (81.6)
Subtype of invasive breast cancer	
Non-triple negative	138 (77.1)
HR-positive and HER2-negative	105 (58.7)
HR-positive and HER2-positive	22 (12.3)
HR-negative and HER2-positive	11 (6.1)
Triple-negative	41 (22.9)
Neoadjuvant chemotherapy	68 (38.0)

Data are presented as mean ± standard deviation or number of patients (%).
*Including 2 apocrine carcinoma, 2 cribriform carcinoma, 2 metaplastic carcinoma, 1 papillary carcinoma, and 1 tubular carcinoma.
IDC = invasive ductal carcinoma, ILC = invasive lobular carcinoma, ER = estrogen receptor, PR = progesterone receptor, HER2 = human epidermal growth factor receptor 2, HR = hormone receptor

In univariable logistic regression analyses, longer intratumoral T2 relaxation times were associated with higher clinical T category, ER negativity, PR negativity, and TNBC subtype (all P < 0.05), regardless of whether measurements included the entire tumor or excluded necrotic or cystic areas (Table 3). Mean intratumoral T2 relaxation times according to clinicopathologic factors are summarized in Supplementary Table 2.

Association Between Peritumoral Edema and Clinicopathologic Characteristics

Clinical T-category distributions differed significantly according to peritumoral edema grades (P < 0.001), with significant differences observed between grade 2 and the other grades (grade 1, P = 0.018; grade 0, P < 0.001), but not between grades 0 and 1 (P = 0.201; Table 2). Tumor ER status differed significantly across peritumoral edema grades (P = 0.009), with a higher proportion of ER-positive cancers among lesions without peritumoral edema (grade 0, 80.9%) compared with grade 1 (59.0%, P = 0.048) and a numerically lower proportion in grade 2 (60.9%, P = 0.060). Similar findings were noted for PR status (overall P = 0.002), with a higher proportion of PR-positive cancers among lesions without peritumoral edema (grade 0, 72.3%) compared with grade 1 (43.6%, P = 0.009) and grade 2 (50.0%, P = 0.048). Although TNBC proportions differed across peritumoral edema grades (P = 0.027), pairwise comparisons did not reach statistical significance (all P > 0.05).

In univariable logistic-regression analysis of the 85 lesions with peritumoral edema (grades 1 or 2), longer T2 relaxation times of the peritumoral-edema region were significantly associated with higher clinical T category (P = 0.005) and ER status (P = 0.030) (Table 3).

Association Between T2 Assessments and NAC Treatment Response

Among the 68 patients who received NAC, 29 (42.6%) had TNBC and 39 (57.4%) had non-TNBC. Disease progression occurred in nine patients (13.2%, 9/68), and pCR was achieved in 21 patients (30.9%, 21/68) (Supplementary Table 3). Of the nine patients with disease progression, two with TNBC underwent MRI because of clinical suspicion, whereas seven were first identified on routine MRI. Among the seven progression cases detected on routine MRI, five patients (two with HR-positive/HER2-negative cancers and three with TNBC) initially demonstrated decreased

 https://doi.org/10.3348/kjr.2025.1382

Table 2. Clinicopathologic characteristics according to grading of intratumoral T2 signal intensity and peritumoral edema

	Intratumoral T2 signal intensity grades							Peritumoral edema grades						
	Grade 0 (n = 93)	Grade 1 (n = 67)	Grade 2 (n = 19)	*P*				Grade 0 (n = 94)	Grade 1 (n = 39)	Grade 2 (n = 46)	*P*			
				Overall	0 vs. 1*	0 vs. 2*	1 vs. 2*				Overall	0 vs. 1*	0 vs. 2*	1 vs. 2*
Clinical T category				0.016	0.012	0.027	>0.999				<0.001	0.201	<0.001	0.018
1	43 (46.2)	27 (40.3)	2 (10.5)					54 (57.4)	14 (35.9)	4 (8.7)				
2	45 (48.4)	34 (50.7)	17 (89.5)					38 (40.4)	23 (59.0)	35 (76.1)				
3	5 (5.4)	6 (9.0)	-					2 (2.1)	2 (5.1)	7 (15.2)				
Multiplicity	37 (39.8)	15 (22.4)	4 (21.1)	0.038	0.597	>0.999	0.096	34 (36.2)	10 (25.6)	12 (26.1)	0.333			
Axillary LN metastasis	27 (29.0)	31 (46.3)	10 (52.6)	0.033	0.252	>0.999	0.114	29 (30.9)	15 (38.5)	24 (52.2)	0.051			
Positive ER	71 (76.3)	44 (65.7)	12 (63.2)	0.249				76 (80.9)	23 (59.0)	28 (60.9)	0.009	0.048	0.060	>0.999
Positive PR	59 (63.4)	37 (55.2)	12 (63.2)	0.557				68 (72.3)	17 (43.6)	23 (50.0)	0.002	0.009	0.048	>0.999
Positive HER2	16 (17.2)	14 (20.9)	3 (15.8)	0.798				14 (14.9)	10 (25.6)	9 (19.6)	0.338			
TNBC vs. non-TNBC				0.282							0.027	0.189	0.081	>0.999
Non-TNBC	76 (81.7)	49 (73.1)	13 (68.4)					80 (85.1)	27 (69.2)	31 (67.4)				
HR+/HER2-	60 (64.5)	35 (52.2)	10 (52.6)					66 (70.2)	17 (43.6)	22 (47.8)				
HR+/HER2+	11 (11.8)	9 (13.4)	2 (10.5)					10 (10.6)	6 (15.4)	6 (13.0)				
HR-/HER2+	5 (5.4)	5 (7.5)	1 (5.3)					4 (4.3)	4 (10.3)	3 (6.5)				
TNBC	17 (18.3)	18 (26.9)	6 (31.6)					14 (14.9)	12 (30.8)	15 (32.6)				

Data are presented as number (%).
*Bonferroni-adjusted *P*-values for multiple comparisons among the three qualitative assessment grades are shown.
LN = lymph node, ER = estrogen receptor, PR = progesterone receptor, HER2 = human epidermal growth factor receptor 2, TNBC = triple-negative breast cancer, HR = hormone receptor

https://doi.org/10.3348/kjr.2025.1382

Korean Journal of Radiology
KJR

Table 3. Associations of T2 relaxation times with clinicopathologic features in univariable logistic regression OR values were calculated for a 10-ms increase in T2 relaxation time

Variables	Clinical T category: T2 or T3 (vs. T1)		Multiplicity		Axillary lymph node metastasis		ER-negative (vs. positive)		PR-negative (vs. positive)		HER2-positive (vs. negative)		TNBC (vs. non-TNBC)	
	OR (95% CI)	*P*	OR (95% CI)	*P*	OR (95% CI)	*P*	OR (95% CI)	*P*	OR (95% CI)	*P*	OR (95% CI)	*P*	OR (95% CI)	*P*
Intratumoral T2 relaxation time (n = 179)														
Whole tumor	1.65 (1.27, 2.20)	<0.001	1.02 (0.86, 1.20)	0.760	1.14 (0.97, 1.36)	0.122	1.27 (1.07, 1.59)	0.015	1.23 (1.04, 1.52)	0.032	1.01 (0.81, 1.20)	0.928	1.29 (1.08, 1.62)	0.011
Avoiding necrotic or cystic areas	1.65 (1.27, 2.22)	<0.001	1.02 (0.81, 1.29)	0.862	1.16 (0.93, 1.47)	0.207	1.58 (1.20, 2.14)	0.002	1.50 (1.17, 1.98)	0.003	1.13 (0.86, 1.50)	0.387	1.61 (1.21, 2.23)	0.002
Peritumoral edema T2 Relaxation Time* (n = 85)	1.61 (1.19, 2.33)	0.005	1.12 (0.92, 1.37)	0.262	1.16 (0.96, 1.41)	0.129	1.25 (1.03, 1.55)	0.030	1.19 (0.98, 1.46)	0.087	0.92 (0.72, 1.14)	0.451	1.17 (0.97, 1.43)	0.109

*Peritumoral edema T2 relaxation time was analyzed in the 85 cases with peritumoral edema (grade 1 or 2).
OR = odds ratio, ER = estrogen receptor, PR = progesterone receptor, HER2 = human epidermal growth factor receptor 2, TNBC = triple-negative breast cancer, CI = confidence interval

lesion size on mid-treatment MRI. However, they were later classified as having disease progression on their final preoperative post-NAC MRI owing to the appearance of new lesions (n = 1) or interval tumor size increase (n = 4), despite the final tumor size being smaller than that measured on baseline MRI.

For progression analysis, Firth's penalized likelihood logistic regression was applied for HER2 status and intratumoral T2 SI grade because of the limited number of events in certain subcategories (HER2-positive and intratumoral T2 SI grade 0). In univariable logistic-regression analysis, disease progression during NAC was associated with higher clinical T category (OR, 9.95; 95% CI, 2.21–53.71; $P = 0.004$), higher intratumoral T2 SI grade (grade 1: OR, 13.49; 95% CI, 1.47–1791.99; $P = 0.017$; grade 2: OR, 29.62; 95% CI, 2.44–4178.06; $P = 0.006$), and longer intratumoral T2 relaxation time excluding necrotic or cystic areas (OR, 1.94; 95% CI, 1.16–3.97; $P = 0.031$; Table 4).

In univariable logistic-regression analysis for non-pCR, only ER negativity (OR, 0.32; 95% CI, 0.10–0.94; $P = 0.046$) showed a significant negative association with pCR (Table 4). PR negativity (OR, 0.36; 95% CI, 0.10–1.07; $P = 0.079$) and intratumoral T2 SI grade 0 (OR, 2.86; 95% CI, 0.94–9.24; $P = 0.069$) showed trends toward, but did not reach, statistical significance.

DISCUSSION

In this study, we investigated the associations between T2WI features—using detailed grading of T2 SI and measurements of T2 relaxation time—and clinicopathologic factors, as well as treatment response to NAC. We found that T2WI features were significantly associated with key clinicopathologic parameters, including clinical T category, HR status, TNBC subtype, and disease progression during NAC. These findings suggest that T2WI, beyond its conventional role in facilitating differential diagnosis, may provide additional prognostic information in the evaluation of breast cancer.

Currently, no standardized criteria exist for classifying T2 SI in breast cancers. Although most studies have defined peritumoral edema as T2 hyperintensity equivalent to that of water [14,15,20,21], the criteria for intratumoral T2 SI have varied—from comparisons with the water signal to those with adjacent breast parenchyma [14,22,23]. Unlike prior studies, we categorized intratumoral T2 SI into three grades and applied a similar three-grade classification to

https://doi.org/10.3348/kjr.2025.1382

Table 4. Univariable logistic regression to examine the association of T2 features and clinicopathologic variables with progression and non-pathologic complete response in patients undergoing neoadjuvant chemotherapy (n = 68)

Variable	Progression		Non-pathologic complete response	
	OR (95% CI)	*P*	OR (95% CI)	*P*
Intratumoral T2 SI grade*				
0	Reference		Reference	
1	13.49 (1.47, 1791.99)	0.017	2.86 (0.94, 9.24)	0.069
2	29.62 (2.44, 4178.06)	0.006	2.80 (0.55, 21.20)	0.248
Intratumoral T2 relaxation time (whole tumor)†	1.47 (1.02, 2.35)	0.051	0.95 (0.70, 1.34)	0.744
Intratumoral T2 relaxation time (avoiding necrotic/cystic areas)†	1.94 (1.16, 3.97)	0.031	0.89 (0.62, 1.22)	0.476
Peritumoral edema grade				
0	Reference		Reference	
1	0.79 (0.03, 8.96)	0.850	0.50 (0.12, 2.02)	0.327
2	2.87 (0.59, 21.04)	0.225	0.74 (0.21, 2.47)	0.628
Clinical T category				
T1	Reference		Reference	
T2 or T3	9.95 (2.21, 53.71)	0.004	1.89 (0.69, 5.64)	0.229
Multiplicity				
No	Reference		Reference	
Yes	0.45 (0.06, 2.05)	0.341	0.69 (0.240, 2.00)	0.487
Axillary lymph node metastasis				
No	Reference		Reference	
Yes	3.51 (0.58, 67.64)	0.252	2.01 (0.65, 6.15)	0.216
ER				
Positive	Reference		Reference	
Negative	1.93 (0.46, 9.84)	0.382	0.32 (0.10, 0.94)	0.046
PR				
Positive	Reference		Reference	
Negative	1.37 (0.33, 7.00)	0.676	0.36 (0.10, 1.07)	0.079
HER2*				
Negative	Reference		Reference	
Positive	0.14 (0.001, 1.21)	0.080	0.33 (0.10, 1.07)	0.064
TNBC vs. non-TNBC				
Non-TNBC	Reference		Reference	
TNBC	1.30 (0.76, 2.39)	0.360	0.43 (0.15, 1.20)	0.110

*HER2 status and intratumoral T2 SI grades were analyzed using Firth's penalized likelihood logistic regression, †OR values were calculated for a 10-ms increase in T2 relaxation time.
HER2 = human epidermal growth factor receptor 2, SI = signal intensity, OR = odds ratio, CI = confidence interval, ER = estrogen receptor, PR = progesterone receptor, TNBC = triple-negative breast cancer

peritumoral edema, consistent with a previous study that demonstrated its association with disease recurrence [7]. The substantial interobserver agreement for both intratumoral T2 SI and peritumoral edema grades supports the feasibility of this grading approach. Furthermore, lesions with higher intratumoral T2 SI or peritumoral edema grades exhibited progressively longer T2 relaxation times, reinforcing the validity of visual assessments in reflecting underlying tissue characteristics such as increased water content or necrotic alterations [8,12]. Given its simplicity and feasibility, T2 visual grading remains a useful method for characterizing tumor biology, showing strong agreement and concordance with quantitative T2 relaxation measurements.

Our findings are consistent with previous studies demonstrating that intratumoral T2 characteristics of breast cancer are associated with aggressive clinicopathologic features [7-9,14,20,22,24,25]. Tumors with grade 2 intratumoral T2 SI were more frequently classified as having a higher clinical T category (89.5% were clinical T2), and the distribution differed significantly between tumors with intratumoral T2 hyperintensity (grades 1–2) and those with grade 0. Longer T2 relaxation times were likewise

https://doi.org/10.3348/kjr.2025.1382

Korean Journal of Radiology
KJR

associated with higher clinical T category, consistent with a previous report showing that central high intratumoral T2 SI was associated with tumors larger than 20 mm [25]. Notably, longer intratumoral T2 relaxation times were also associated with HR negativity and the TNBC subtype, even after exclusion of necrotic or cystic areas, whereas T2 grading did not show such associations. These findings suggest that T2 relaxation time of intratumoral T2 SI may more accurately reflect characteristics related to tumor immunohistochemical subtypes.

Higher peritumoral-edema grades were significantly associated with aggressive tumor characteristics, including higher clinical T category, HR negativity, and a greater proportion of TNBC, consistent with previous studies [7,15]. A recent study further reported that peritumoral edema correlated with lymphovascular invasion, vascular ectasia, stromal fibrosis, reduced infiltrative growth, and tumor necrosis [20]. Our findings therefore reinforce the concept that peritumoral edema reflects aggressive tumor biology. However, T2 relaxation times of peritumoral edema were associated only with clinical T category and ER status, suggesting that visual grading of peritumoral edema alone may suffice for clinical interpretation.

Among patients who received NAC, the overall disease progression rate was 13.2% (9/68) and was higher among those with TNBC (20.7%, 6/29). This higher rate may have been influenced by our institutional protocol, which included breast MRI examinations before treatment, during mid-treatment, and after completion of NAC. In this study, where MRI was performed at three standardized time points, the nadir corresponded to either the baseline or the mid-treatment MRI; therefore, progression was determined based on this nadir-based comparison rather than solely against the baseline MRI. Only two patients with TNBC underwent MRI because of clinical suspicion, whereas 44.4% of progression cases (4/9) were identified based on interval changes after the mid-treatment MRI, despite smaller final tumor sizes than those recorded at baseline. When considering only lesions that demonstrated progression relative to the baseline MRI, the progression rate among patients with TNBC (10.3%, 3/29) was comparable to that reported in a recent study in which MRI was performed only before and after NAC, where 85% of progression cases were clinically detected [26]. Nonetheless, the higher progression rate observed in our study likely reflects differences in patient selection and imaging protocol. This limitation should be considered when interpreting our results.

Baseline T2WI features were evaluated as potential predictors of treatment response, particularly disease progression during NAC. Predicting progression from baseline imaging could have important clinical implications, such as enabling closer surveillance during NAC or consideration of early surgical intervention. Disease progression during NAC was associated with higher intratumoral T2 SI grades and longer intratumoral T2 relaxation times, measured after exclusion of necrotic or cystic components. These findings suggest that both intratumoral T2 SI grades and T2 relaxation time may serve as noninvasive imaging biomarkers of poor treatment responsiveness. In contrast, T2 features were not significantly associated with non-pCR, for which only ER negativity showed an inverse association. Nonetheless, intratumoral T2 characteristics may contribute to multiparametric breast MRI models for early identification of non-responders to NAC. Further studies are warranted to validate and expand upon these findings in diverse patient populations [11,27].

Our study has several limitations. First, its retrospective, single-center design may have introduced selection bias. Second, analysis of T2 relaxation time relied on manual segmentation; automated approaches may enhance feasibility and robustness. Third, the relatively small number of patients who received NAC precluded response analysis according to immunohistochemical subtype. Given variations in chemotherapy regimens and pCR rates among subtypes, results may differ when analyzed separately. The limited sample size may also restrict the generalizability of findings within the NAC subgroup, underscoring the need for validation in larger cohorts. Fourth, Ki-67 was not analyzed because it is not routinely reported in biopsy specimens at our institution, and the study population included both NAC and non-NAC patients. Fifth, the relatively high progression rate during NAC may reflect our frequent MRI monitoring, limited sample size, and the inherent selection bias of a retrospective, single-center design. Larger, prospective studies are warranted to confirm these results. Finally, although OR values for T2 relaxation time were expressed per 10-ms increase, this scaling is arbitrary, and proportionally smaller OR values would be obtained if calculated for smaller increments (e.g., 1 ms).

In conclusion, T2-weighted MRI features were associated with clinical T category, HR status, TNBC subtype, and disease progression during NAC. Notably, intratumoral T2 relaxation times demonstrated similar associations even after exclusion of necrotic or cystic areas, suggesting their potential to reflect tumor characteristics beyond necrosis.

 https://doi.org/10.3348/kjr.2025.1382

As breast MRI continues to evolve toward multiparametric and non–contrast-enhanced approaches, incorporating T2-weighted parameters may contribute to improved prognostication and more personalized treatment strategies.

Supplement

The Supplement is available with this article at https://doi.org/10.3348/kjr.2025.1382.

Availability of Data and Material

The datasets generated or analyzed during the study are available from the corresponding author on reasonable request.

Conflicts of Interest

The authors have no potential conflicts of interest to disclose.

Author Contributions

Conceptualization: Vivian Youngjean Park. Data curation: Inyoung Youn, Min Jung Kim, Jung Hyun Yoon, Vivian Youngjean Park. Formal analysis: Inyoung Youn, Yun Ho Roh, Vivian Youngjean Park. Funding acquisition: Vivian Youngjean Park. Investigation: Inyoung Youn, Vivian Youngjean Park. Methodology: Inyoung Youn, Yun Ho Roh, Vivian Youngjean Park. Project administration: Vivian Youngjean Park. Resources: Min Jung Kim, Vivian Youngjean Park. Supervision: Vivian Youngjean Park. Visualization: Inyoung Youn, Vivian Youngjean Park. Writing—original draft: Inyoung Youn, Vivian Youngjean Park. Writing—review & editing: all authors.

ORCID IDs

Inyoung Youn
https://orcid.org/0000-0002-3518-3332
Yun Ho Roh
https://orcid.org/0000-0003-0841-7161
Min Jung Kim
https://orcid.org/0000-0003-4949-1237
Jung Hyun Yoon
https://orcid.org/0000-0002-2100-3513
Mi-ri Kwon
https://orcid.org/0000-0001-8225-3690
Vivian Youngjean Park
https://orcid.org/0000-0002-5135-4058

Funding Statement

This study was supported by a faculty research grant of Yonsei University College of Medicine for 2022 (6-2022-0162).

Acknowledgments

We thank Yeon Ju Ahn and Seung Yeop Yang for their assistance with data collection and data handling.

REFERENCES

1. Mann RM, Cho N, Moy L. Breast MRI: state of the art. *Radiology* 2019;292:520-536
2. Choi EJ, Choi H, Choi SA, Youk JH. Dynamic contrast-enhanced breast magnetic resonance imaging for the prediction of early and late recurrences in breast cancer. *Medicine (Baltimore)* 2016;95:e5330
3. Nam SY, Ko ES, Lim Y, Han BK, Ko EY, Choi JS, et al. Preoperative dynamic breast magnetic resonance imaging kinetic features using computer-aided diagnosis: association with survival outcome and tumor aggressiveness in patients with invasive breast cancer. *PLoS One* 2018;13:e0195756
4. Bae MS, Bernard-Davila B, Sung JS, Morris EA. Preoperative breast MRI features associated with positive or close margins in breast-conserving surgery. *Eur J Radiol* 2019;117:171-177
5. Pötsch N, Sodano C, Baltzer PAT. Performance of diffusion-weighted imaging-based noncontrast MRI protocols for diagnosis of breast cancer: a systematic review and meta-analysis. *Radiology* 2024;311:e232508
6. Partridge SC, Rahbar H, Murthy R, Chai X, Kurland BF, DeMartini WB, et al. Improved diagnostic accuracy of breast MRI through combined apparent diffusion coefficients and dynamic contrast-enhanced kinetics. *Magn Reson Med* 2011;65:1759-1767
7. Cheon H, Kim HJ, Kim TH, Ryeom HK, Lee J, Kim GC, et al. Invasive breast cancer: prognostic value of peritumoral edema identified at preoperative MR imaging. *Radiology* 2018;287:68-75
8. Seo M, Ryu JK, Jahng GH, Sohn YM, Rhee SJ, Oh JH, et al. Estimation of T2* relaxation time of breast cancer: correlation with clinical, imaging and pathological features. *Korean J Radiol* 2017;18:238-248
9. Gibson AL, Watkins JE, Agrawal A, Tyminski MM, DeBenedectis CM. Shedding light on T2 bright masses on breast MRI: benign and malignant causes. *J Breast Imaging* 2022;4:430-440
10. Grimm LJ, Enslow M, Ghate SV. Solitary, well-circumscribed, T2 hyperintense masses on MRI have very low malignancy rates. *J Breast Imaging* 2019;1:37-42
11. Kim S, Kim MJ, Kim EK, Yoon JH, Park VY. MRI radiomic features: association with disease-free survival in patients with triple-negative breast cancer. *Sci Rep* 2020;10:3750
12. Harada TL, Uematsu T, Nakashima K, Kawabata T, Nishimura S,

Takahashi K, et al. Evaluation of breast edema findings at T2-weighted breast MRI is useful for diagnosing occult inflammatory breast cancer and can predict prognosis after neoadjuvant chemotherapy. *Radiology* 2021;299:53-62
13. Liang T, Hu B, Du H, Zhang Y. Predictive value of T2-weighted magnetic resonance imaging for the prognosis of patients with mass-type breast cancer with peritumoral edema. *Oncol Lett* 2020;20:314
14. Jirarayapong J, Portnow LH, Chikarmane SA, Lan Z, Gombos EC. High peritumoral and intratumoral T2 signal intensity in HER2-positive breast cancers on preneoadjuvant breast MRI: assessment of associations with histopathologic characteristics. *AJR Am J Roentgenol* 2024;222:e2330280
15. Panzironi G, Moffa G, Galati F, Marzocca F, Rizzo V, Pediconi F. Peritumoral edema as a biomarker of the aggressiveness of breast cancer: results of a retrospective study on a 3 T scanner. *Breast Cancer Res Treat* 2020;181:53-60
16. Liu L, Yin B, Shek K, Geng D, Lu Y, Wen J, et al. Role of quantitative analysis of T2 relaxation time in differentiating benign from malignant breast lesions. *J Int Med Res* 2018;46:1928-1935
17. Eisenhauer EA, Therasse P, Bogaerts J, Schwartz LH, Sargent D, Ford R, et al. New response evaluation criteria in solid tumours: revised RECIST guideline (version 1.1). *Eur J Cancer* 2009;45:228-247
18. Litton JK, Regan MM, Pusztai L, Rugo HS, Tolaney SM, Garrett-Mayer E, et al. Standardized definitions for efficacy end points in neoadjuvant breast cancer clinical trials: NeoSTEEP. *J Clin Oncol* 2023;41:4433-4442
19. Landis JR, Koch GG. The measurement of observer agreement for categorical data. *Biometrics* 1977;33:159-174
20. Park NJ, Jeong JY, Park JY, Kim HJ, Park CS, Lee J, et al. Peritumoral edema in breast cancer at preoperative MRI: an interpretative study with histopathological review toward understanding tumor microenvironment. *Sci Rep* 2021;11:12992
21. Kwon BR, Shin SU, Kim SY, Choi Y, Cho N, Kim SM, et al. Microcalcifications and peritumoral edema predict survival outcome in luminal breast cancer treated with neoadjuvant chemotherapy. *Radiology* 2022;304:310-319
22. de Paula IB, Pena GP, Barbosa AL, Oliveira GJP, Ferreira SS, Cordeiro LPV. Intratumoral intensity in T2-weighted MRI and the association with histological and molecular prognostic factors in women with invasive breast cancer. *J Breast Imaging* 2021;3:315-321
23. Kanao S, Kataoka M, Iima M, Ikeda DM, Toi M, Togashi K. Differentiating benign and malignant inflammatory breast lesions: value of T2 weighted and diffusion weighted MR images. *Magn Reson Imaging* 2018;50:38-44
24. Bae MS, Shin SU, Ryu HS, Han W, Im SA, Park IA, et al. Pretreatment MR imaging features of triple-negative breast cancer: association with response to neoadjuvant chemotherapy and recurrence-free survival. *Radiology* 2016;281:392-400
25. Dietzel M, Baltzer PA, Vag T, Herzog A, Gajda M, Camara O, et al. The necrosis sign in magnetic resonance-mammography: diagnostic accuracy in 1,084 histologically verified breast lesions. *Breast J* 2010;16:603-608
26. Yoen H, Kim SY, Lee DW, Lee HB, Cho N. Prediction of tumor progression during neoadjuvant chemotherapy and survival outcome in patients with triple-negative breast cancer. *Korean J Radiol* 2023;24:626-639
27. Park H, Lim Y, Ko ES, Cho HH, Lee JE, Han BK, et al. Radiomics signature on magnetic resonance imaging: association with disease-free survival in patients with invasive breast cancer. *Clin Cancer Res* 2018;24:4705-4714

 https://doi.org/10.3348/kjr.2025.1382