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3-T Breast Diffusion-Weighted MRI by Echo-Planar Imaging with Spectral Spatial Excitation or with Additional Spectral Inversion Recovery: An In Vivo Comparison of Image Quality

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Abstract

Objective—To compare conventional DWI with spectral spatial excitation (cDWI) and an enhanced DWI with additional adiabatic spectral inversion recovery (eDWI) for 3T breast MRI.

Methods—Twenty-four patients were enrolled in the study with both cDWI and eDWI. Three breast radiologists scored cDWI and eDWI images of each patient for fat-suppression quality, geometric distortion, visibility of normal structure and biopsy-proven lesions, and overall image quality. SNR, CNR and ADC for evaluable tissues were measured. Statistical tests were performed for qualitative and quantitative comparisons.

Results—eDWI yielded significantly higher CNR and SNR on a lesion and higher glandular CNR and SNR, and muscle SNR on a patient basis. eDWI also yielded significantly higher qualitative scores in all categories. No significant difference was found in ADC values.

Conclusion—eDWI provided superior image quality and higher CNR and SNR on a lesion basis. eDWI can replace cDWI for 3T breast DWI.

Keywords

Breast MRI; diffusion-weighted imaging; echo-planar imaging; spectral spatial excitation; adiabatic spectral inversion

INTRODUCTION

Magnetic resonance imaging (MRI) is a well-established and highly useful adjunct to mammography and ultrasonography for detecting and evaluating breast malignancy. With

conventional T1-weighted, T2-weighted, and dynamic contrast-enhanced (DCE) sequences, the sensitivity of MRI for detecting certain invasive breast cancers is very high, at 94%–99%^{1–4}. However, the specificity is substantially lower, ranging from 37% to 86%^{3–5}. This large disparity in sensitivity and specificity is a serious limitation to breast MRI and an improvement in specificity could help reduce the number of patients who may be subject to increased anxiety or even unnecessary biopsies.

Diffusion-weighted imaging (DWI), which is sensitive to the random motion of water molecules in tissues^{6, 7}, offers an alternative and potentially complementary contrast mechanism. The signal intensity of DWI is sensitized to diffusion through application of a pair of diffusion gradients that is characterized by a user-selectable b -value (in unit of s/mm^2)⁸. By acquiring DWI images at two or more b -values, it is possible to derive a quantitative apparent diffusion coefficient (ADC) map for which the pixel values are reflective of only the diffusion property of the tissue. Because malignant lesions in general are believed to have reduced diffusion as a result of increased cellularity and increased tortuosity in extracellular matrix, DWI has been hypothesized and successfully used⁹ to better differentiate between benign and malignant lesions in several parts of the body. For breast imaging, DWI may improve the positive predictive value compared with that of DCE MRI alone¹⁰.

DWI is most widely implemented with single-shot echo-planar imaging (EPI) due to its speed and ability to freeze motion¹¹. Unfortunately, single-shot EPI is also extremely sensitive to resonance offsets such as those from the magnetic field inhomogeneity and chemical shift of fat, which can be problematic in breast imaging. The conventional method for removing the fat signal in EPI is through the use of the spectral spatial radiofrequency (RF) pulse¹², which ideally excites only the water magnetization with a 2D slice and leaves the fat magnetization unperturbed. Unfortunately, the performance of the spectral spatial RF pulse can be severely compromised in the presence of large B0 or B1 inhomogeneity. While the effect of B0 inhomogeneity does not directly scale with B0 (because the chemical shift [in Hertz] also increases with B0), B1 inhomogeneity for breast imaging can be substantially increased at 3 T due to the increased dielectric effect¹³. Another fat-suppression technique widely used with EPI and other pulse sequences is short tau inversion recovery (STIR)¹⁴. One main advantage of STIR is its insensitivity to B0 inhomogeneity. STIR can also be insensitive to B1 inhomogeneity when an adiabatic inversion RF pulse is used. However, conventional STIR suffers from reduced signal-to-noise ratio (SNR) and thus is not particularly desirable for DWI.

A few studies have examined the different fat-suppression techniques for breast DWI, including their potential impact on quantitative ADC calculations^{5, 15–17}. Wenkel et al⁵ compared DWI with CHESS and with STIR and found that lesion visibility was significantly better with CHESS than with STIR. Additionally, the ADC values from DWI with CHESS were lower than the ADC values from DWI with STIR, and only the ADC values by CHESS were able to differentiate between benign and malignant lesions. In comparison, Kazama et al¹⁶ found that the ADC values from DWI with CHESS were higher than those from DWI with STIR and that fat suppression with CHESS was insufficient in 44% of the patients in their study. In another study, Baron et al¹⁵ reported

only small differences between the ADC values from DWI with several different fat-suppression techniques and that DWI with spectral water excitation yielded the highest SNR.

The purpose of our study was to evaluate and compare several qualitative image quality metrics (fat-suppression uniformity, anatomic visibility, geometric distortion, and radiologist preference) as well as a few quantifiable measurements (SNR, CNR and ADC values) by using DWI images from EPI with spectral spatial excitation (cDWI) or from EPI with additional spectral inversion recovery (eDWI). The two sets of DWI images of each patient were acquired at 3 T in a single MRI study as a part of her routine clinically indicated breast MRI.

MATERIALS AND METHODS

Patients

This study was conducted as a clinical performance quality improvement (PQI) project to optimize the image quality of our institution's routine breast MRI. Approval for retrospective chart review was obtained from the Institutional Review Board (IRB) and HIPPA compliance was strictly adhered to. In total, twenty four patients were enrolled in the study. All the patients were scheduled for a conventional breast MRI exam and were selected on the basis of the availability of the MRI scanners and the protocoling radiologists. Mean patient age was 53.4 ± 11.4 years (range, 25–78 years). Twenty biopsy-proven lesions (8 malignant, 8 benign, and 4 benign post-surgical scars) were found in 11 women. Thirteen patients had had no discrete lesions on pre- and post-contrast DCE MRI sequences. Additionally, one woman with a malignant lesion and a benign lesion was scanned with the two different DWI sequences several months apart and thus was excluded from the analysis because changes might have occurred due to chemotherapy between the two studies.

Breast DWI

All 24 study participants, who had a clinical indication for either high-risk cancer screening or treatment monitoring, underwent conventional breast MRI at our institution. The conventional MRI included a pre-contrast T1-weighted imaging sequence, a fat-suppressed T2-weighted sequence, and a DCE sequence with a fat-suppressed T1-weighted sequence. A cDWI sequence used a single-shot EPI readout and a spectral spatial excitation RF pulse for fat suppression. This sequence was part of the standard MRI protocol that was used in our institution at the time of our study. An eDWI sequence, which had an additional adiabatic spectral inversion RF pulse before spin excitation, was added to the standard protocol as a clinical quality improvement project. Both cDWI and eDWI sequences were acquired in the axial plane. Detailed scan parameters are given in Table 1. Parallel imaging (ASSET) with an acceleration factor of 2 was used in the phase encoding direction (left/right) for both sequences. Between 48 and 90 images were acquired for each of the cDWI and eDWI sequences, depending on the patient's size.

The number of images and most parameters were kept the same in both DWI sequences for each patient. A notable difference was that b -values of 0 and 1000 s/mm^2 were used in

cDWI and b -values of 100 and 800 s/mm² were used in eDWI. At the time of our study, only one non-zero b -value was allowed on the scanner for each acquisition by cDWI. With the increased flexibility in eDWI, we chose a b -value of 100 s/mm² to minimize potential contamination in the ADC calculation due to the presence of microperfusion or intravoxel incoherent motion¹⁸. All studies were performed on one of the two 3.0-T identically configured whole-body MRI scanners (GE Signa, GE Medical Systems, Waukesha, WI) and with an eight-channel high-density dedicated breast coil (GE Signa, GE Medical Systems, Waukesha, WI).

Quantitative Analysis

One radiologist (B.E.D) with 12 years of experience in breast MRI performed the quantitative image analysis for all 24 study participants. For each patient, normal anatomical structure (including the signal intensity of the pectoral muscle, an axillary lymph node, and normal glandular tissue) was measured from the images of different b -values. A region of interest (ROI) for normal glandular tissue and muscle was first identified and placed on the image with the higher of the two b -values used and then copied to the image with the lower b -value. The ROI for the lymph node was placed on an index axillary node. The normal tissue and muscle ROIs were placed in a central slice containing the nipple. ROIs were placed on the same slice and anatomic location in both cDWI and eDWI images while accounting for patient motion between scans and potentially different geometric distortions if necessary. The same ROIs were also placed in the ADC maps that were generated on the scanner to measure the ADC values for the glandular tissue, muscle, and lymph node (Figure 1). Care was taken to avoid partial volume effects on a given ROI. Additionally, a large circular ROI was placed in a region of uniform noise to measure its standard deviation^{19, 20}. SNR was calculated for the muscle and normal tissue using Equation 1, and contrast-to-noise ratio (CNR) between the two tissue types was calculated according to Equation 2^{19, 20}. For CNR calculations, the muscle region was chosen as tissue type 2 because of the signal void in fat-saturated areas surrounding the normal breast tissue.

$$\text{SNR} = \frac{S_{\text{tissue}}}{\sigma_{\text{background}}} \quad [1]$$

$$\text{CNR} = \frac{(S_{\text{tissue1}} - S_{\text{tissue2}})}{\sigma_{\text{background}}} \quad [2]$$

Signal intensity and ADC values were also measured from any lesions that were present in order to calculate their CNR. Measurements were made only in biopsy-proven lesions.

Qualitative Analysis

The same reader and two additional radiologists (B.E.A. and J.S.P, with 7 and 5 years of experience in breast MRI, respectively) also assessed the cDWI and eDWI images using the qualitative scores of 1–5 on the following image quality features: fat-suppression quality, geometric distortion, visibility of normal structures, and overall image quality. In 11 patients with breast lesions, each lesion was given a visibility score for both cDWI and eDWI scans.

The scales used for the image quality categories were adapted from a 2011 study by Dogan et al.²¹ and are described in Table 2. Generally speaking, a score of 1 corresponds to the worst performance and a score of 5 corresponds to the best performance²¹. Besides scoring for individual patients, each radiologist also recorded a final subjective preference between the two DWI sequences for each study on the basis of their overall assessment of image quality.

Statistical Analysis

Due to the observed skewness in the data, ADC, SNR, and CNR were transformed to the logarithmic scale for analysis. A linear mixed model was used to compare each endpoint between cDWI and eDWI. The mixed model took into account correlations between measurements from the same lesion or from the same patient. Mean and corresponding 95% confidence intervals were estimated by the linear mixed model. Model estimates were back-transformed to the raw scale for presentation. The qualitative scores were summarized in frequencies and percentages by the techniques and readers. Kappa statistics was calculated for each imaging quality between the readers. Multivariate linear mixed model was used to compare the quality scores adjusting for reader effects and taking into account the correlation between ratings from the same images. All tests were two-sided and p-values less than 0.05 were considered statistically significant. Statistical analysis was carried out using SAS version 9 (SAS Institute, Cary, NC).

RESULTS

Quantitative Analysis

Statistically significant differences in mean estimates between cDWI and eDWI results were found for glandular CNR (7.31 vs. 19.22; $P = 0.003$), glandular SNR (18.18 vs. 36.80; $P < 0.0001$), and muscle SNR (9.30 vs. 14.21; $P = 0.0004$) (Table 3). There were no statistically significant differences in ADC between the two DWI sequences or in lymph node CNR.

The estimated mean CNR for all lesions was statistically significantly different for cDWI and eDWI (30.29 vs. 50.21, $P = 0.002$) (Table 4). The estimated mean ADC value for all lesions was not statistically significantly different (1343.72 vs. 1424.39 mm²/s; $P = 0.34$).

Qualitative Analysis

Out of the twenty four patient exams, the three radiologists selected eDWI as the preferred pulse sequence in 22, 24, and 23 cases, respectively. Of the two studies in which eDWI was not rated as the preferred sequence by one radiologist, one had very poor image quality on both cDWI and eDWI and neither image was deemed to be of adequate diagnostic quality. For the second patient study, cDWI and eDWI were considered of equally good quality due to successful fat suppression in both sequences.

Mean scores by all three readers for fat-suppression quality, geometric distortion, normal structure visibility, and overall image quality were approximately twice as high with eDWI than with cDWI (Table 5).

Kappa statistics for the different evaluated image quality categories and the two DWI techniques revealed mostly slight (kappa: 0.01–0.20) to fair (kappa: 0.21–0.40) inter-observer agreement. Multivariate linear mixed model was therefore used to compare eDWI and cDWI adjusting for reader effects. Further, the linear mixed model took into account correlations between ratings from the same images. The analysis revealed that despite a significant difference between readers, eDWI had significantly higher scores than cDWI in all the evaluated categories (Table 6).

DISCUSSION

Although diffusion-weighted MRI has been used more frequently for extracranial applications in the last few years, image quality from a clinical setting can still be inconsistent and suboptimal. In our experience, fat-suppression failure is a primary source of image quality degradation for breast DWI. There are several different fat suppression options that are currently available and used for DWI. To the best of our knowledge, our study was the first to qualitatively and quantitatively compare cDWI and eDWI for breast DWI at 3T in the same group of patients. In our study, we found that adding an adiabatic spectrally selective inversion recovery pulse to a spectral-spatial water excitation pulse in the pulse sequence consistently improved the quality and robustness of fat suppression for breast DWI at 3 T, as indicated by both significantly improved SNR and CNR by quantitative assessment and higher qualitative scoring. Conventional STIR can be insensitive to both B0 and B1 inhomogeneity and has been shown to improve the uniformity of fat suppression in breast DWI. However, conventional STIR suffers from a low SNR, which was shown by Wenkel et al ⁵ to reduce lesion visibility and ADC values. The adiabatic spectrally selective inversion RF pulse used in our study retains the advantage of STIR for being insensitive to B1 inhomogeneity while preserving the water signal for SNR. While both the spectral spatial excitation pulse and the adiabatic spectral inversion pulse are B0 sensitive, our results are consistent with a recent report in which a combination of the two pulses provided more robust and consistent fat suppression than did using spectral spatial excitation pulse alone for fat-suppressed high-resolution T1-weighted breast imaging at 3 T ²².

In our analysis, the two DWI sequences for each study participant were acquired in the same imaging session. Since the patient setup was identical between the two sequences, we expected that any differences in image quality and quantitative ADC values we observed would be caused by differences in the two techniques. Indeed, the two sequences were acquired in succession with minimal gross patient motion, which facilitated easy and direct slice-to-slice comparison and copying of ROIs between the two sequences that required little adjustment (Figure 2). The clear technical advantage of eDWI over cDWI was reflected by the eDWI qualitative scores that were approximately double those of cDWI in all four categories.

The eDWI sequence was also found to be more robust than the cDWI sequence. Two patients in our study required a repeat cDWI sequence with re-prescription of shim volumes and manual pre-scan due to poor fat saturation. Unfortunately, for both cases the quality was only marginally improved. In comparison, one eDWI sequence was repeated and fat

suppression was noted to have greatly improved. As a result of the improvements in image quality and consistency, the Breast Imaging Section in our institution has since replaced cDWI with eDWI in the standard-of-care clinical protocol for breast MRI at 3 T.

Two limitations of our study were the relatively small number of patients for which both cDWI and eDWI sequences of each patient were performed on the same day and the small number of biopsy-proven lesions that were available for analysis. A larger number of patients with more lesions that are evaluable could have been enrolled in the study. However, performing two DWI sequences increases the total scan time and could have compromised patient tolerance. Nevertheless, our study findings are supported by the generally more favorable impression of our institution's reading radiologists in the Breast Section on breast DWI image quality, and the fewer "non-useable" breast DWI images after cDWI have been replaced with eDWI in the routine clinical protocol for 3-T breast MRI at our institution.

We used two slightly different sets of b -values for cDWI and eDWI in our study. For cDWI, we kept the b -values of 0 and 1000 s/mm² of the original clinical protocol. For eDWI, we used 100 s/mm² for the low b -value acquisition because it increases flexibility in the sequence and because it can help minimize potential microperfusion effects on ADC calculation²³, and we used 800 s/mm² rather than 1000 s/mm² for the high b -value acquisition to improve the SNR. While microperfusion and the image SNR can both affect ADC calculations, microperfusion is minimal and does not affect ADC values in breast fibroglandular tissues¹⁵. In our study, we found that ADC values of the different tissues were generally higher in eDWI than in cDWI, although none of the differences were statistically significant. However, the quality of the DWI images as related to fat suppression and ghosting can directly affect ADC values (Figure 3). Among the tissue regions evaluated, the largest ADC difference between the two DWI sequences was in the lymph node; however, the ADC values may not be sufficiently accurate in cDWI because of the large variability in image quality.

In summary, in comparison to cDWI, eDWI provided superior image quality for breast DWI at 3 T and higher CNRs and SNRs, particularly on a per-lesion basis. Despite no statistically significant difference in quantitative ADC values, eDWI can replace cDWI for routine clinical breast DWI at 3 T.

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Figure 1.

Normal tissue and muscle ROIs were placed in a central slice containing the nipple. ROIs were placed on the same slice and anatomic location on both cDWI and eDWI images (a and b). The same ROIs were also placed in the ADC maps (c) that were generated on the scanner to measure the ADC values for glandular tissue, muscle, and lymph node.

Figure 2.

Two different slices of diffusion-weighted images by cDWI and eDWI from a 65-year-old woman presenting for magnetic resonance evaluation of therapy response. cDWI images at $b = 1000 \text{ s/mm}^2$ (a and c) demonstrated poor fat suppression throughout the breast and resulted in hypointense glandular tissues due to inadvertent water suppression. The eDWI images at $b = 800 \text{ s/mm}^2$ (b and d) showed uniform fat suppression and demonstrated much better visibility of a malignant lesion (circle) compared with the cDWI image in (c). eDWI images (b and d) also better depicted the pectoral muscle than the cDWI images did (a and c).

Figure 3.

DWI image and corresponding calculated ADC map between cDWI and eDWI from a 71-year-old woman with a history of cancer in the left breast presenting for screening. (a) Bilateral cDWI image at $b = 1000 \text{ s/mm}^2$ showed unsuppressed and displaced fat signal, significant geometric distortion, and low CNR for glandular tissue (arrow) in the right breast. (b) The poor DWI image rendered the ADC map unreliable in the right breast. (c) Bilateral eDWI image at $b = 800 \text{ s/mm}^2$ demonstrated much improved image quality and CNR of glandular tissues compared with the cDWI image in (a). (d) ADC map generated from the eDWI image showed better quality and was more consistent between the left and the right breasts.

Table 1

Scan Parameters Used for cDWI and eDWI Sequences

Scan parameter	cDWI	eDWI
TI	N/A	200ms
TR	3900–7075 ms	4700–7125 ms
TE	69.8–72.7 ms	57.4–60.4 ms
Acquisition matrix	160×256	128×192
NEX	4	4
Slice thickness	5.0 mm	5.0 mm
Slice gap	0 mm	0 mm
<i>b</i> -value		
Low	0 s/mm ²	100 s/mm ²
High	1000 s/mm ²	800 s/mm ²

Table 2

Scales for Qualitative Analysis

Score	Fat-suppression quality	Geometric distortion	Normal structure* visibility	Overall image quality	Lesion visibility**
5	Uniform throughout field of view	None	All structures delineated	Best	Very confidently assessed
4	Slight inhomogeneities	Slight distortion present	Nipple not visualized, all other structures delineated	Good	Confidently assessed
3	Inhomogeneities present, but not preventing assessment	Double breast in one breast	Pectoral muscle and nipple delineation not clear	Fair	Not confidently assessed
2	Inhomogeneity affects clinical assessment	Double breast in both breasts	Decreased lymph node contrast	Poor	Lesion present, features indeterminate
1	Inhomogeneity prevents diagnostic evaluation	No correlation with anatomical structure	Lack of delineation prevents assessment	Non-diagnostic	Non-diagnostic

* Lymph nodes, pectoral muscle, nipple.

** Only assessed for patients with biopsy-proven lesions. Each lesion was given an individual score.

Table 3

Linear Mixed Model Results Comparing Estimated Mean (95% Confidence Interval) ADC, CNR, and SNR for cDWI and eDWI

Endpoint and Sequence	Mean (95% confidence interval)	P value
Glandular ADC*		0.10
cDWI	1469.09 (1298.81–1661.54)	
eDWI	1619.71 (1514.29–1732.64)	
Glandular CNR		0.003
cDWI	7.31 (4.84 – 11.06)	
eDWI	19.22 (13.09 – 28.22)	
Glandular SNR		<0.0001
cDWI	18.18 (14.67 – 22.54)	
eDWI	36.80 (29.75 – 45.53)	
Muscle ADC*		0.51
cDWI	1201.47 (867.23 – 1664.53)	
eDWI	1332.75 (1163.86 – 1525.99)	
Muscle SNR		0.0004
cDWI	9.30 (9.19 – 10.56)	
eDWI	14.21 (11.12 – 18.16)	
Node ADC*		0.28
cDWI	1037.01 (758.39 – 1418.00)	
eDWI	1277.81 (987.13 – 1654.08)	
Node CNR		0.25
cDWI	23.64 (15.39 – 36.30)	
eDWI	32.47 (18.12 – 58.17)	

* Unit of measures for ADC is mm²/s.

Table 4

Linear Mixed Model Results Comparing Estimated Mean (95% Confidence Interval) ADC and CNR for cDWI and eDWI for Evaluable Lesions

Endpoint and Sequence	Mean (95% confidence interval)	P value
ADC*		0.34
cDWI	1343.72 (1161.54 –1554.49)	
eDWI	1424.39 (1228.81 –1650.94)	
CNR		0.002
cDWI	30.29 (19.68 – 46.61)	
eDWI	50.21 (28.47 – 88.56)	

* Unit of measures for ADC is mm²/s.

Table 5

Qualitative scoring results by readers

	Readers	Fat-Suppression Quality	Geometric Distortion	Normal Structure Visibility	Overall Image Quality
eDWI	A	2.00 ± 1.06	1.83 ± 0.92	2.21 ± 0.93	2.00 ± 0.93
	B	2.00 ± 0.88	1.29 ± 0.55	1.75 ± 0.85	1.63 ± 0.71
	C	2.88 ± 0.95	1.92 ± 0.93	2.42 ± 0.96	2.29 ± 0.81
eDWI	A	4.38 ± 1.01	4.33 ± 1.09	4.17 ± 1.13	4.21 ± 1.10
	B	3.63 ± 0.49	3.13 ± 0.61	3.38 ± 0.58	3.42 ± 0.50
	C	4.29 ± 0.75	3.58 ± 0.72	4.13 ± 0.85	4.00 ± 0.78

Table 6
Linear mixed model analysis of the differences of the quality scores between cDWI and eDWI

	Comparison	Estimated Mean Difference	95% LCL	95% UCL	P-value
Fat Suppression Quality	cDWI vs. eDWI	-1.81	-2.09	-1.52	<.0001
	Readers A vs. C	-0.40	-0.74	-0.05	0.02
	Readers B vs. C	-0.77	-1.11	-0.43	<.0001
Geometric Distortion	cDWI vs. eDWI	-2.00	-2.26	-1.74	<.0001
	Readers A vs. C	0.33	0.03	0.64	0.03
	Readers B vs. C	-0.54	-0.85	-0.24	0.00
Normal Structure Visibility	cDWI vs. eDWI	-1.76	-2.03	-1.50	<.0001
	Readers A vs. C	-0.08	-0.40	0.23	0.59
	Readers B vs. C	-0.71	-1.02	-0.40	<.0001
Overall Image Quality	cDWI vs. eDWI	-1.90	-2.15	-1.66	<.0001
	Readers A vs. C	-0.04	-0.33	0.25	0.77
	Readers B vs. C	-0.63	-0.91	-0.34	<.0001