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Kinetic Curves of Malignant Lesions Are Not Consistent Across MRI Systems: Need for Improved Standardization of Breast Dynamic Contrast-Enhanced MRI Acquisition

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Abstract

OBJECTIVE—The purpose of this study was to compare MRI kinetic curve data acquired with three systems in the evaluation of malignant lesions of the breast.

MATERIALS AND METHODS—The cases of 601 patients with 682 breast lesions (185 benign, 497 malignant) were selected for review. The malignant lesions were classified as ductal carcinoma in situ (DCIS), invasive ductal carcinoma (IDC), and other. The dynamic MRI protocol consisted of one unenhanced and three to seven contrast-enhanced images acquired with one of three imaging protocols and systems. An experienced radiologist analyzed the shapes of the kinetic curves according to the BI-RADS lexicon. Several quantitative kinetic parameters were calculated, and the kinetic parameters of malignant lesions were compared across the three systems.

RESULTS—Imaging protocol and system 1 were used to image 304 malignant lesions (185 IDC, 62 DCIS); imaging protocol and system 2, 107 lesions (72 IDC, 21 DCIS); and imaging protocol and system 3, 86 lesions (64 IDC, 17 DCIS). Compared with those visualized with imaging protocols and systems 1 and 2, IDC lesions visualized with imaging protocol and system 3 had significantly less initial enhancement, longer time to peak enhancement, and a slower washout rate ($p < 0.004$). Only 47% of IDC lesions imaged with imaging protocol and system 3 exhibited washout type curves, compared with 75% and 74% of those imaged with imaging protocols and systems 2 and 1, respectively. The diagnostic accuracy of kinetic analysis was lowest for imaging protocol and system 3, but the difference was not statistically significant.

CONCLUSION—The kinetic curve data on malignant lesions acquired with one system showed significantly lower initial contrast uptake and a different curve shape in comparison with data acquired with the other two systems. Differences in k-space sampling, T1 weighting, and magnetization transfer effects may be explanations for the difference.

Keywords

breast; dynamic contrast-enhanced MRI; malignant lesions; kinetic parameters; standardization

Dynamic contrast-enhanced MRI (DCE-MRI) of the breast is being used increasingly for a variety of clinical purposes, including post-treatment evaluation, evaluation of the extent of malignant disease, and screening of women at high risk for developing breast cancer [1–3]. The advantage of DCE-MRI is its high sensitivity, particularly for early invasive tumors. This

benefit is important because detection of breast cancer at an earlier stage can greatly improve outcome [4]. Unfortunately, the specificity of DCE-MRI has been reported to be variable [2]. In addition, there is concern that the diagnostic accuracy of DCE-MRI for the earliest stage of breast cancer, ductal carcinoma in situ (DCIS), may not be high [5]. Results [6,7] have suggested that on both these counts, DCE-MRI performs comparably with or better than x-ray mammography. However, the perceived or actual limitations combined with the increased cost of DCE-MRI have limited the widespread use of MRI in the care of patients with breast cancer [8,9].

At DCE-MRI, lesions are characterized according to both morphologic characteristics and contrast uptake and washout kinetics. The ability of DCE-MRI to depict cancerous lesions is governed mostly by whether the lesion exhibits sufficient contrast enhancement to be discerned from normal tissue. The specificity of DCE-MRI lies in the accuracy of morphologic and kinetic descriptors in identification of malignant lesions. In an effort to improve the specificity of DCE-MRI, the kinetic and morphologic characteristics of malignant and benign lesions have been extensively studied [10–16]. In addition, multicenter trials have been conducted to evaluate the diagnostic efficacy of kinetic and morphologic parameters and to determine the features most useful for interpretation of breast DCE-MR images [17,18]. Results of such studies have helped in formation of the two following general principles of interpretation of DCE-MRI kinetic data that are designed to help improve specificity: The first general principle is that malignant lesions tend to exhibit rapid uptake and washout, whereas benign lesions have slower uptake and persistent contrast uptake over time [19,20]. The second general principle is that the kinetic characteristics of DCIS are variable, overlapping considerably with those of benign lesions and showing slower contrast uptake and washout than invasive ductal carcinoma (IDC) [5,21–25].

Standardization of breast MRI acquisition is not widespread. That is, there are no universally applied quality assurance procedures to ensure that as newer MRI systems are used clinically, the measured kinetic curves continue to satisfy the two general principles. There are several manufacturers of MRI systems, and the various systems have differing k-space sampling methods, pulse sequences, and coils that continue to be modified and improved over time. Furthermore, dynamic imaging protocols differ among institutions as to timing resolution, use of fat suppression, plane of acquisition, use of parallel imaging, and imaging protocols. Yet radiologists and imaging physicists should expect that the two general principles outlined above be applicable in all clinical acquisitions so that similar interpretation criteria can be applied and similar diagnostic accuracy can be achieved, even as newer technology (such as parallel imaging, newer k-space sampling techniques, and computer-aided detection systems) is implemented. At our institution, we are in a unique position to address these concerns. Here, breast MRI has been performed with three different MRI systems, and we maintain a database of all MRI-detected lesions imaged with the three systems. The purpose of this study was to validate the two general principles with different MRI systems and to determine whether, absent standardization procedures, malignant lesions have similar manifestations on images obtained with all three systems.

Materials and Methods

Patients

At our institution, DCE-MRI is performed for several reasons, including preoperative staging, evaluation after chemotherapy, and screening of women at high risk. We prospectively maintain a HIPAA-compliant database that includes the MRI morphologic findings, kinetic curve data, and subsequent pathologic results, when available, on all lesions detected in women enrolled with an institutional review board–approved waiver of consent or informed consent process. A retrospective review of this database yielded, in 601 patients, 682 consecutively

detected lesions eligible for study that had pathologic findings based on biopsy or final pathology reports. Images were acquired from May 2002 to April 2007. The average patient age was 56 ± 13.5 years. After review of pathology reports, 497 lesions were determined to be malignant and 185 benign.

MRI Protocols

DCE-MRI has been performed at our institution with the three systems outlined in Table 1. From May 2002 to August 2005, patients were imaged with imaging protocol and system 1. From September 2005 to April 2007, the protocol and system 1 were replaced with two new protocols and systems that were used concurrently. Although the two new systems were from different manufacturers (GE Healthcare and Philips Healthcare), collaborative efforts of breast radiologists and MRI physicists were undertaken to ensure that similar parameters and techniques would be used for both protocols and systems so that comparable images would be obtained. For all patients, the first contrast-enhanced images were acquired 20 seconds after IV injection of 20 mL of 0.5 M of gadodiamide (Omniscan, GE Healthcare) followed by a 20-mL saline flush at the rate of 2.0 mL/s.

Kinetic Analysis

Signal intensity versus time—or kinetic—curves for each lesion were retrospectively generated in two ways. For lesions acquired with imaging protocol and system 1, kinetic curves were generated by an experienced radiologist using institutional software. Specifically, the radiologist viewed all slices containing the lesion and manually traced a region of interest (ROI) around what was perceived to be the most enhancing area of the lesion in a single slice. The average size of manually drawn ROIs was 7.4 pixels. For lesions acquired with imaging protocols and systems 2 and 3, the kinetic curves were extracted from a commercially available computer-aided detection system (CADstream version 5.0, Confirma). In addition to assigning color maps to lesions, the software generated a volumetric ROI encompassing the lesion and selected the most suspicious curve (that is, the one with the most rapid uptake and washout) in a 3×3 pixel ROI within the volume. This representative curve and its corresponding ROI were examined by the same radiologist and manually modified if necessary. In case a lesion was not recognized by the computer-aided detection software, the radiologist manually selected an ROI on what was perceived to be the most enhancing area of the lesion. Although the temporal resolution of the scans obtained with each system differed somewhat (Table 1), the last time point was similar for all protocols and was used to determine the delayed phase.

Having generated the kinetic curve, the radiologist classified the initial rise of the curve according to the BI-RADS lexicon as rapid, medium, or slow and the delayed phase as persistent, plateau, or washout. This judgment was based on a purely qualitative assessment of curve shape with the radiologist blinded to the pathologic finding of the lesion. In addition, several quantitative parameters were calculated for each curve: initial enhancement percentage, peak enhancement percentage, time to peak enhancement, and signal enhancement ratio, a measure of washout. Further details on these parameters are presented in Appendix 1.

Statistical Analysis

Our aim was to evaluate the two general principles noted earlier. Because three different MRI systems were used, we performed this evaluation separately for each system. Each lesion was classified as having been imaged with protocol and system 1, 2, or 3. In addition, the pathologic finding on each malignant lesion was assigned IDC, DCIS, or other on the basis of review of pathology reports.

We began by studying the kinetic curves of malignant and benign lesions imaged with the same protocol and system. The qualitative BI-RADS descriptors of initial rise and delayed phase

were compared for benign and malignant lesions by use of the chi-square test for significance, $p < 0.05$ indicating significance. The Student's t test was used to test for differences in the quantitative parameters—initial enhancement percentage, peak enhancement percentage, signal enhancement ratio, and time to peak enhancement—for benign and malignant lesions, $p < 0.05$ indicating significance. The Holm-Bonferroni correction was used for multiple comparisons. The Student's t test also was used to compare values of initial enhancement percentage, peak enhancement percentage, signal enhancement ratio, and time to peak enhancement for DCIS versus IDC and DCIS versus benign lesions.

We evaluated whether the assessment of contrast kinetics was affected by the protocol and system used. The qualitative descriptors of malignant and benign lesions imaged with protocols and systems 1, 2, and 3 were compared by use of the chi-square test; the quantitative parameters were compared by use of the Student's t test. The diagnostic accuracy of the kinetic parameters was evaluated separately for each protocol. For the qualitative BI-RADS descriptors, the sensitivity and specificity of rapid uptake, washout, and washout–plateau were calculated. Receiver operating characteristic analysis was performed to evaluate the diagnostic performance of the quantitative kinetic parameters. Software (Rockit 0.9B beta version, Charles E. Metz, University of Chicago [26]) was used to generate the receiver operating characteristic curves and for comparison of areas under the curve (A_z) by use of the area test.

Results

Overall, most of the lesions—137 benign and 304 malignant—were imaged with protocol and system 1. Of the other benign lesions, 21 were imaged with protocol and system 2 and 27 with protocol and system 3. Of the remaining malignant lesions, 107 were imaged with protocol and system 2 and 86 with protocol and system 3. Most of the malignant lesions were classified IDC (Table 2). DCIS lesions composed approximately 20% of malignant lesions imaged with protocols and systems 1, 2, and 3. Final pathology reports after lumpectomy or mastectomy were available for 81 of 100 DCIS lesions; the other 19 lesions were classified as DCIS after biopsy alone. After review of final pathology reports, 66% (66/100) of DCIS lesions were determined to be pure DCIS; 5% (5/100), DCIS with microinvasion; and 10% (10/100), geographically separated from an ipsilateral invasive tumor. The rest of the malignant lesions classified as other were 31 invasive lobular carcinomas, 26 unspecified carcinomas, three invasive tubular carcinomas, seven lesions of Paget's disease of the nipple, two invasive papillary carcinomas, three inflammatory carcinomas, three mucinous carcinomas, and one colloid carcinoma. Examples of malignant IDC lesions acquired with imaging protocols and systems 1, 2, and 3 and the corresponding kinetic curves are shown in Figure 1.

BI-RADS Assessment of Curve Shape

Kinetic curves of malignant lesions imaged with protocol and system 1 exhibited a higher proportion, 89%, of curves with a rapid initial rise, compared with 55% of benign lesions ($p < 0.0001$) (Table 2). Malignant lesions imaged with protocols and systems 2 and 3 exhibited comparable proportions of rapid curves compared with their benign counterparts. For all three protocols, a higher proportion of malignant than benign lesions had washout curves ($p < 0.004$) (Table 2). Comparable proportions of DCIS lesions imaged with protocols and systems 1 and 3 exhibited washout, plateau, and persistent curve shapes, whereas most DCIS lesions imaged with protocol and system 2 were classified as having a washout or plateau curve (Table 2).

Although malignant and benign lesions imaged with each protocol exhibited differences in delayed phase characteristics, the actual frequencies of BI-RADS descriptors—for example, the proportion of curves classified rapid or washout—varied among protocols. For example, malignant lesions imaged with protocol and system 3 exhibited a slightly lower proportion, 81%, of curves classified rapid initial rise compared with malignant lesions imaged with

protocols and systems 1 and 2 (Table 2). Notably, assessment of the delayed phase revealed a marked difference: 69% and 66% of malignant lesions imaged with protocols and systems 2 and 1 were classified as washout, respectively, compared with only 44% of those imaged with protocol and system 3 ($p < 0.0008$) (Fig. 2B). This finding was repeated for IDC lesions separately: only 47% of IDC lesions imaged with protocol and system 3 were classified as washout compared with 75% and 74% of IDC lesions imaged with protocols and systems 2 and 1, respectively (Table 2).

Quantitative Kinetic Parameters

The qualitative observations were further confirmed in quantitative analysis. Benign lesions imaged with protocol and system 1 exhibited a lower initial enhancement percentage and signal enhancement ratio and a longer time to peak enhancement than did malignant lesions imaged with the same protocol ($p < 10^{-6}$) (Table 3). The peak enhancement percentage also was lower for benign lesions, but the difference was not significant. Benign lesions imaged with protocols and systems 2 and 3 also exhibited trends similar to those of their malignant counterparts. After Holm-Bonferroni correction for multiple comparisons, initial enhancement percentage and peak enhancement percentage were significant for lesions imaged with protocol and system 2 ($p < 0.004$). No parameters were found statistically significant among lesions imaged with protocol and system 3.

In the comparison of the kinetic parameters of DCIS with those of other lesions, we found that DCIS lesions imaged with protocol and system 1 exhibited lower initial enhancement percentage, peak enhancement percentage, and signal enhancement ratio and longer time to peak enhancement than did IDC lesions imaged with the same protocol ($p < 0.0008$) (Table 3). However, DCIS and benign lesions exhibited considerable overlap in all parameters. There was a trend for DCIS to have lower initial and peak enhancement percentages and a higher signal enhancement ratio than benign lesions, but the differences were not significant after Holm-Bonferroni correction. The latter finding persisted for imaging protocols and systems 2 and 3: DCIS and benign lesions did not exhibit significant differences. However, unlike lesions imaged with protocol and system 1, lesions imaged with protocol and system 2 or 3 did not exhibit a significant difference in the kinetics parameters of DCIS and IDC.

After analysis of the kinetic characteristics of benign and malignant lesions in each imaging protocol, the kinetic parameters were compared between protocols. According to the qualitative BI-RADS classification of curve shape, malignant lesions imaged with protocol and system 3 exhibited fewer rapid and washout curve types. This finding was amplified at quantitative analysis. Malignant lesions imaged with protocol and system 3 exhibited significantly lower initial ($p < 10^{-5}$) and peak ($p = 0.004$) enhancement percentages and signal enhancement ratio ($p < 10^{-22}$) and longer time to peak enhancement ($p = 0.003$) than those imaged with imaging protocol and system 1. Compared with malignant lesions imaged with protocol and system 2, malignant lesions imaged with protocol and system 3 also exhibited lower initial and peak enhancement percentages, signal enhancement ratio, and time to peak enhancement, and after Holm-Bonferroni correction, the initial and peak enhancement percentages remained significant ($p < 0.001$) (Table 3). Malignant lesions imaged with protocol and system 2 also had a lower signal enhancement ratio than did those imaged with protocol and system 1 ($p = 0.002$). Otherwise we found no significant difference in kinetic parameters between imaging protocols and systems 1 and 2.

Diagnostic Accuracy of Kinetic Parameters With Different Imaging Protocols

The discrepancies found in the kinetic characteristics of malignant lesions between the three protocols studied led us to investigate the effect on the diagnostic accuracy of kinetic analysis. Considering the descriptors washout and plateau indicative of malignancy, the sensitivity of

these descriptors in imaging protocols and systems 1, 2, and 3 was 88% (95% CI, 83–91%), 93% (95% CI, 85–97%), and 85% (95% CI, 75–91%), respectively. The specificity was 41% (95% CI, 33–50%), 45% (95% CI 28–64%), and 37% (CI, 20–58%). In other words, the diagnostic accuracy of the BI-RADS descriptors typically used to identify malignant lesions was reduced for imaging protocol and system 3, although not significantly.

Receiver operating characteristic analysis of the diagnostic accuracy of the parameters initial enhancement percentage, peak enhancement percentage, signal enhancement ratio, and time to peak enhancement yielded A_z values showing a trend for compromised diagnostic performance with imaging protocol and system 3 (Fig. 3). There was a trend for signal enhancement ratio to be less useful diagnostically in imaging protocol and system 3 versus system 1, while the diagnostic performance of peak enhancement percentage improved with imaging protocol and system 2 compared with the others. These differences, however, were not statistically significant. The highest A_z value for imaging protocol and system 3 was 0.64 for time to peak enhancement, for imaging protocol and system 2 was 0.68 for initial enhancement percentage, and for imaging protocol and system 1 was 0.73 for signal enhancement ratio.

Discussion

We set out to evaluate whether kinetic curve data acquired with three MRI protocols and systems satisfied two principles pertaining to the interpretation of DCE-MRI kinetic data. The first principle, related to the general curve shape of malignant lesions (rapid uptake and washout) compared with benign lesions (persistent uptake), met with uneven success. We found that in the largest database of lesions imaged with the older protocol and system 1, both of these observations held true: most of the malignant lesions were classified as washout, whereas persistent was the most likely descriptor of benign lesions. Most malignant lesions imaged with protocol and system 2 also were classified as washout, but only 19% of benign lesions were classified as persistent. More important, with imaging protocol and system 3, fewer than one half of kinetic curves of malignant lesions were classified washout. Although it is certainly important to recognize and address these differences, the effect on the diagnostic accuracy of kinetic parameters was not drastic: there was a trend for compromised sensitivity and specificity with imaging protocol and system 3, but it was not statistically significant. In addition, imaging protocol and system 1 had a considerably greater number of lesions than the other two systems, which may have affected our results.

The second principle pertained to the kinetic characteristics of DCIS, which have been reported to be variable, to overlap with benign lesions, and to exhibit marked differences in uptake and washout compared with IDC. We found that the kinetic variability of DCIS was validated in the larger database acquired with imaging protocol and system 1, in which DCIS had 44% washout, 22% plateau, and 34% persistent curve types—in other words, all curve types were found. Similarly, DCIS lesions imaged with protocol and system 3 had 29% washout, 30% plateau, and 41% persistent curve types. However, lesions imaged with protocol and system 2 had less variability: 62% (13/21) of DCIS lesions were classified as washout, 33% (7/21) as plateau, and only 5% (1/21) as persistent. We found that the quantitative kinetic parameters of benign and DCIS lesions exhibited overlap in all three protocols and systems. However, only DCIS and IDC lesions imaged with protocol and system 1 had statistically significant differences from one another.

Overall, we found that the typical kinetic presentation of malignant lesions is not consistent across MRI systems, representing a potential clinical problem. For example, our results imply that in follow-up MRI of women undergoing preoperative neoadjuvant chemotherapy, it is important to perform follow-up imaging with the system used initially, lest differences due to

system choice be mistaken for tumor response. Every effort was taken in this study to reproduce similar MRI acquisition protocols on the three systems, particularly for imaging protocols and systems 2 and 3, which were used concurrently. With both systems, images were acquired with fat suppression, similar dynamic timing, parallel imaging, and similar T1 weighting. We emphasize that we are not suggesting that MRI systems from one manufacturer are preferable to those from another. Nor are we challenging the two general principles. Rather, our results emphasize the importance of improving standardization procedures [20,27], so that all women undergoing breast DCE-MRI can be imaged adequately to ensure that malignant lesions will become sufficiently enhanced and exhibit similar curve shapes. We are designing experimental phantoms for this purpose.

The differences in average kinetic parameters across the three protocols and systems may be attributable to numerous factors. One may be that kinetic curves were not generated the same way for every lesion. Images acquired with protocol and system 1 were displayed and analyzed with institutional software, whereas images from protocols and systems 2 and 3 were analyzed with a commercially available computer-aided detection system. This limitation, however, is applicable only to comparisons of imaging protocol and system 1 with the others. It cannot explain the differences between results on malignant lesions imaged with protocols and systems 3 and 2, because DCE-MRI data were processed and analyzed the same way for the two systems. Specifically, the markedly lower initial enhancement percentage and signal enhancement ratio and the smaller fraction of washout curves for malignant lesions imaged with protocol and system 3—less than one half—is likely not attributable to use of a computer-aided detection system for analysis of kinetic data. The lower initial enhancement percentage and differences in overall curve shape may be due to other effects, such as fat suppression, parallel imaging, postacquisition processing, and k-space sampling techniques. It may be that displaying contrast concentration rather than signal intensity may help to eliminate intersystem variability. We are exploring these and other potential factors by imaging the same lesions with different systems and imaging protocols.

There were several limitations to this study. Already mentioned is that curve selection was not performed in a uniform manner for all lesions. Another shortcoming was that the benign lesions in this study were histologically proven benign, that is, they were suspicious enough to warrant biopsy. It may be that with increased experience, the radiologists' evaluations of borderline benign cases improved, and hence the benign lesions included in imaging protocols and systems 2 and 3 were even more suspicious than those included in imaging protocol and system 1, resulting in a biased sample of lesions. In addition, the reliability of the kinetic parameters peak enhancement percentage and time to peak enhancement may have been compromised by the several timing acquisitions used and by the coarse sampling of kinetic data. The parameters initial enhancement percentage and signal enhancement ratio are not as adversely affected by these two concerns because they depend on signal intensities measured at the initial and last time points, which occur at similar times for all protocols. Finally, we did not evaluate morphologic features in this study. For full assessment of the diagnostic accuracy of DCE-MRI, morphologic descriptors must be included.

This study showed that in one large database of kinetic data on 441 malignant and benign lesions acquired with an older system, the two general principles regarding lesion kinetics hold. Unfortunately, the principles are not consistently applicable to lesions imaged with other systems. The kinetic curves of malignant lesions acquired with one newer system exhibited lower initial uptake and fewer washout curves than did those acquired with the other two systems. The markedly lower initial enhancement percentage for lesions, whether malignant or benign, imaged with system 3 is important to note and address. The results of this study emphasize the importance of standardization of DCE-MRI acquisition protocols so that as newer technology is implemented, malignant lesions are sufficiently conspicuous and similar

interpretation guidelines can be consistently applied across all systems and protocols. Such standardization is important if breast DCE-MRI is to be used routinely in patient care.

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APPENDIX 1

Calculation of Quantitative Parameters

Percentage enhancement is a measure of the uptake of contrast material in the lesion relative to the signal intensity level before contrast enhancement [13], as follows:

$$E_1 = 100 \times \frac{S_1 - S_0}{S_0}$$

$$E_{peak} = 100 \times \frac{S_{peak} - S_0}{S_0},$$

where E_1 is the initial percentage enhancement, E_{peak} is the peak percentage enhancement, S_1 is the signal intensity in the region of interest at the first contrast-enhanced point, S_{peak} is the peak signal intensity, and S_0 is the unenhanced signal intensity in the region of interest. The time to peak enhancement is the time in seconds between injection of contrast material and the peak of the signal intensity–time curve.

The parameter used to quantify washout is the signal enhancement ratio, which is a measure of the relative decrease in signal intensity from the first contrast-enhanced time point to the final contrast-enhanced point [28,29], as follows:

$$SER = \frac{S_1 - S_0}{S_{last} - S_0}$$

where SER is the signal enhancement ratio and S_{last} is the signal intensity in the region of interest at the last point of contrast enhancement. The signal enhancement ratio parameter is used to quantify the washout in the curve through choice of threshold values. A signal

enhancement ratio less than 0.9 means that the final signal intensity increases in relation to the first contrast-enhanced point (persistent increase). A signal enhancement ratio of 0.9–1.1 indicates the final signal intensity is comparable with the first contrast-enhanced point (plateau). A signal enhancement ratio greater than 1.1 indicates that the final signal intensity decreases in relation to the first contrast-enhanced point (washout).

Fig 1. Examples of MR images and kinetic curves obtained with three systems and protocols
A and B, 57-year-old woman with invasive ductal carcinoma (*arrow*). MR image (**A**) and kinetic curve (**B**) acquired with imaging protocol and system 1 have the following quantitative parameters: initial enhancement percentage, 334%; peak enhancement percentage, 350%; signal enhancement ratio, 1.21; time to peak enhancement, 249 seconds. **C and D**, 54-year-old woman with invasive ductal carcinoma (*arrow*). MR image (**C**) and kinetic curve (**D**) acquired with imaging protocol and system 2 have the following quantitative parameters: initial enhancement percentage, 282%; peak enhancement percentage, 360%; signal enhancement ratio, 0.92; time to peak enhancement, 118 seconds. **E and F**, 73-year-old woman with invasive ductal carcinoma (*arrow*). MR image (**E**) and kinetic curve (**F**) acquired with imaging protocol

and system 3 have the following quantitative parameters: initial enhancement percentage, 107%; peak enhancement percentage, 221%; signal enhancement ratio, 0.55; time to peak enhancement, 120 seconds.

Fig 2. Contrast enhancement of malignant lesions

A and B, Graphs show percentage of lesions with BI-RADS descriptor of kinetic curve shape during initial rise (**A**) and delayed phase (**B**) on MR images acquired with imaging protocols and systems 1, 2, and 3.

Fig 3.

Graph shows area under curve (A_z) for four kinetic parameters: time to peak enhancement (T_{peak}), signal enhancement ratio (SER), peak enhancement percentage (E_{peak}), and initial enhancement percentage (E_1). For each parameter, three A_z values are presented for imaging protocols and systems (IPS) 1, 2, and 3. Error bars indicate 95% CI.

TABLE 1

Summary of MRI Systems and Protocols

Characteristic	System 1	System 2	System 3
Dates used	May 2002–September 2005	September 2005–April 2007	September 2005–April 2007
Unit	1.5-T Genesis Signa (GE Healthcare)	1.5-T Signa Excite (GE Healthcare)	1.5-T Achieva (Philips Healthcare)
No. of coil channels	4	8	7
Acquisition plane	Coronal	Axial	Axial
Pulse sequence	3D spoiled gradient-recalled echo	3D fast gradient-recalled echo	3D fast-field echo
TR/TE	7.7/4.2	4.3/2.0	7.9/3.9
Flip angle	30°	10°	10°
Slice thickness (mm)	3.00	2.00	2.00
In-plane resolution (mm)	1.4	0.82	0.94
Temporal resolution (s)	68	58	55
No. of contrast-enhanced images	3 or 5 ^a	4 or 6	4 or 6 ^b
Fat suppression	No	Yes	Yes
Parallel imaging	No	Yes	Yes

^aFirst acquisition was started 20 seconds after contrast injection, and the first two contrast-enhanced images were acquired every 68 seconds. For the five-point dynamic protocol, the other three images were acquired with 68-second resolution. For the three-point dynamic protocol, the first two contrast-enhanced acquisitions were followed by acquisition of high-spatial-resolution sagittal images for 128 seconds and then a final dynamic 68-second acquisition.

^bFor imaging protocols and systems 2 and 3, the first contrast-enhanced acquisition was started 20 seconds after contrast injection and the first three contrast-enhanced images were acquired every 58 seconds (55 seconds, protocol 3). For the six-point dynamic protocol, the other three images were acquired with 58- or 55-second resolution. For the four-point dynamic protocol, the first two contrast-enhanced acquisitions were followed by acquisition of high-spatial-resolution sagittal images and a final dynamic acquisition.

TABLE 2
BI-RADS Descriptors of Initial Rise and Delayed Phase for Benign and Malignant Lesions Acquired With Three Systems

Type of Lesion	No. of Cases	Initial Rise			Delayed Phase			<i>p</i> ^a	
		Rapid	Medium	Slow	Washout	Plateau	Persistent		
Imaging protocol and system 1									
Benign	137	75 (55)	25 (18)	37 (27)	42 (31)	39 (28)	56 (41)	< 0.0001	
All malignant	304	270 (89)	22 (7)	12 (4)	202 (66)	64 (21)	38 (13)		
DCIS	62	43	12	7	27	14	21		
IDC	185	177	4	4	137	36	12		
Other	57	50	6	1	38	14	5		
Imaging protocol and system 2									
Benign	21	18 (86)	3 (14)	0 (0)	6 (29)	11 (52)	4 (19)	0.001	
All malignant	107	98 (92)	7 (7)	2 (2)	74 (69)	25 (23)	8 (7)		
DCIS	21	16	5	0	13	7	1		
IDC	72	70	2	0	54	14	4		
Other	14	12	0	2	7	4	3		
Imaging protocol and system 3									
Benign	27	20 (74)	3 (11)	4 (15)	3 (11)	14 (52)	10 (37)	0.004	
All malignant	86	70 (81)	13 (15)	3 (3)	38 (44)	35 (41)	13 (15)		
DCIS	17	11	3	3	5	5	7		
IDC	64	55	9	0	30	29	5		
Other	5	4	1	0	3	1	1		

Note—Values in parentheses are percentages. DCIS = ductal carcinoma in situ, IDC = invasive ductal carcinoma. Numbers in parentheses are percentages.

^aComparison of washout, plateau, and persistent curve shapes for benign and malignant lesions.

TABLE 3
Quantitative Kinetic Parameters of Benign and Malignant Lesions Acquired With Three Systems

Type of Lesion	No. of Cases	Initial Enhancement (%)	Peak Enhancement (%)	Time to Peak Enhancement (s)	Signal Enhancement Ratio
Imaging protocol and system 1					
Benign	137	204 ± 158	302 ± 192	233 ± 107	0.76 ± 0.36
All malignant	304	286 ± 158	330 ± 155	165 ± 105	1.07 ± 0.48
DCIS	62	194 ± 138	252 ± 147	222 ± 108	0.89 ± 0.44
IDC	185	313 ± 151	352 ± 149	144 ± 98	1.15 ± 0.50
Imaging protocol and system 2					
Benign	21	163 ± 78	221 ± 82	198 ± 102	0.81 ± 0.23
All malignant	107	245 ± 214	301 ± 213	178 ± 126	0.94 ± 0.32
DCIS	21	219 ± 189	269 ± 197	209 ± 201	0.97 ± 0.31
IDC	72	264 ± 236	319 ± 232	160 ± 96	0.97 ± 0.33
Imaging protocol and system 3					
Benign	27	61 ± 38	149 ± 56	251 ± 110	0.45 ± 0.28
All malignant	86	122 ± 281	213 ± 356	211 ± 100	0.57 ± 0.33
DCIS	17	119 ± 204	187 ± 192	241 ± 125	0.62 ± 0.45
IDC	64	125 ± 309	223 ± 401	203 ± 91	0.56 ± 0.26