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Abbreviated MRI of the Breast: Does It Provide Value?

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MRI of the breast is the most sensitive test for breast cancer detection and outperforms conventional imaging with mammography, digital breast tomosynthesis, or ultrasound. However, the long scan time and relatively high costs limit its widespread use. Hence, it is currently only routinely implemented in the screening of women at an increased risk of breast cancer. To overcome these limitations, abbreviated dynamic contrast-enhanced (DCE)-MRI protocols have been introduced that substantially shorten image acquisition and interpretation time while maintaining a high diagnostic accuracy. Efforts to develop abbreviated MRI protocols reflect the increasing scrutiny of the disproportionate contribution of radiology to the rising overall healthcare expenditures. Healthcare policy makers are now focusing on curbing the use of advanced imaging examinations such as MRI while continuing to promote the quality and appropriateness of imaging. An important cornerstone of value-based healthcare defines value as the patient's outcome over costs. Therefore, the concept of a fast, abbreviated MRI exam is very appealing, given its high diagnostic accuracy coupled with the possibility of a marked reduction in the cost of an MRI examination. Given recent concerns about gadolinium-based contrast agents, unenhanced MRI techniques such as diffusion-weighted imaging (DWI) are also being investigated for breast cancer diagnosis. Although further larger prospective studies, standardized imaging protocol, and reproducibility studies are necessary, initial results with abbreviated MRI protocols suggest that it seems feasible to offer screening breast DCE-MRI to a broader population. This article aims to give an overview of abbreviated and fast breast MRI protocols, their utility for breast cancer detection, and their emerging role in the new value-based healthcare paradigm that has replaced the fee-for-service model.

Level of Evidence: 1

Technical Efficacy: Stage 2

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Breast cancer is one of the leading causes of death among women in the United States, with early detection of cancer being the key to improved prognosis and survival. Randomized controlled trials have found that screening mammography has decreased the mortality for breast cancer by 30%.[1] However, with a sensitivity of ~70%, mammography has its limitations. Particularly in women with dense breasts, cancers might be occult on mammography.[2] Magnetic resonance imaging (MRI) of the breast is undisputedly the most sensitive of imaging methods to detect cancer, with a higher cancer detection rate than mammography, digital breast tomosynthesis, and ultrasound. Adjunct screening with dynamic contrast-enhanced (DCE)-MRI was first recommended for women at high (>20%) lifetime risk of breast cancer,[3–5] facilitating earlier cancer detection and reducing interval cancers[6–15] in this population. This prompted a most recent similar recommendation for its use in women at intermediate (>15%) lifetime risk of breast cancer.[16] Meanwhile, for women at average risk of breast cancer, there is evidence that they might also benefit from screening MRI. Kuhl et al investigated the utility of MRI as a supplemental screening tool in 2120 women at average breast cancer risk, and found that MRI depicted 60 additional breast cancers, while 12 of 13 incident cancers were found with MRI alone.[17]

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Despite such encouraging results, breast MRI is currently not implemented in the screening of women at average risk of breast cancer, with the limiting factor being its relatively high direct and indirect costs and widespread availability compared with conventional imaging.[18,19]

Apart from the initial purchase price of the MRI equipment, major drivers of the high costs of breast MRI are the relatively long acquisition, limiting high-volume patient throughput and interpretation times involved in a full diagnostic protocol. In efforts to overcome these limitations and facilitate increased access to screening breast MRI, Kuhl et al initially introduced an abbreviated breast MRI protocol for screening that substantially shortened examination and reading times; at the same time, this protocol maintained a diagnostic accuracy equivalent to a full diagnostic protocol.[20] Thereafter, several other studies have investigated different abbreviated and high-temporal resolution MRI protocols for breast cancer diagnosis and screening, with similar results.[21–42] This review will provide an overview of the current published literature on abbreviated breast MRI and its potential clinical applications and challenges. We will also discuss the emerging roles of fast temporal resolution, unenhanced MRI strategies in an abbreviated MR protocol, and workflow issues to implement abbreviated MR exams into the clinical workflow.

DCE-MRI of the Breast

DCE-MRI allows the assessment of high-resolution breast morphology and enhancement kinetics to depict angiogenesis as a tumor-specific feature.[43] At any given field strength, DCE-MRI is the most sensitive modality for breast cancer detection, with a pooled sensitivity of 93%; DCE-MRI has good pooled specificity of 71%.[5,6,44–46]

In high-risk women, several studies have demonstrated that DCE-MRI is the superior screening modality compared with conventional imaging techniques. Schrading et al[47] demonstrated that MRI had both high specificity and positive predictive value. Obdeijn et al[48] found a sensitivity of 93.6% for MRI alone in a population of 93 *BRCA1* mutation-carriers, with mammography giving no additional value to MRI screening in women below the age of 40. Riedl et al[49] demonstrated that MRI in high-risk patients had a sensitivity of 90%, and almost half of all cancers (45%) in their cohort were detected by MRI only. Similar results were found by Krammer et al.[50]

Central to breast cancer detection using DCE-MRI is the combination of morphological features and functional information derived from enhancement kinetics; this need is supported by multiple studies and noted in the revised MR Breast Imaging Reporting and Data System (BI-RADS) lexicon.[51,52] There is consensus that the ideal breast MRI protocol should incorporate both a high spatial and high temporal resolution MRI protocol. Such a protocol enables simultaneous and accurate assessment of lesion morphology and lesion enhancement kinetics and optimizes sensitivity and specificity. However, these are two competing demands: a high spatial resolution protocol requires thinner slices for better delineation of breast morphology, ultimately leading to longer acquisition times.[51] A high temporal resolution (acquisition speed) protocol requires faster acquisition speeds for a more accurate depiction of enhancement kinetics, leading to a tradeoff in the assessment of morphologic features.

In the clinical setting, breast DCE-MRI protocols attempt to balance between the two demands, with most protocols including a three-plane localizer sequence, T_2-weighted or short inversion time (TI) inversion recovery (STIR) sequence, T_1-weighted precontrast sequence, or three or more T_1-weighted postcontrast sequences. Sequences are performed with or without fat saturation, while post-processing usually include subtraction and maximum intensity projection (MIP) images. Currently, full diagnostic protocols are used uniformly for indications such as preoperative staging, detection of scar versus recurrence, response assessment and therapy monitoring of neoadjuvant chemotherapy, cancer of unknown primary, and assessment of equivocal findings on conventional imaging.[3,53,54] Currently, there is no recommendation on protocol adjustments when breast DCE-MRI is used solely for screening purposes.[5,55]

Abbreviated MRI

As mentioned, Kuhl et al in 2014 were the first to report on the feasibility of an abbreviated breast MRI protocol for breast cancer screening, consisting of an unenhanced T_1-weighted and first contrast-enhanced T_1-weighted sequence, subtraction imaging, and a single MIP image.[20] This abbreviated protocol was generated from a full diagnostic protocol in 606 examinations of 443 women; the two protocols were compared regarding acquisition time, cancer yield, and diagnostic accuracy (Fig. 1). This groundbreaking study found that image acquisition and interpretation time could be reduced without having a negative impact on diagnostic accuracy. With the abbreviated MRI protocol, the acquisition time was substantially decreased to 3 minutes, compared with 17 minutes for the full diagnostic protocol. The interpretation time of the abbreviated protocol was 28 seconds on average and 2.8 seconds when the MIP image alone was evaluated (the interpretation time for the full protocol was not measured). If compared with mammography, the average interpretation time for the abbreviated MRI protocol proved to be much faster than the interpretation of screening mammography of 2–4 minutes.[56] Of 606 MRI studies, all 11 cancers were found

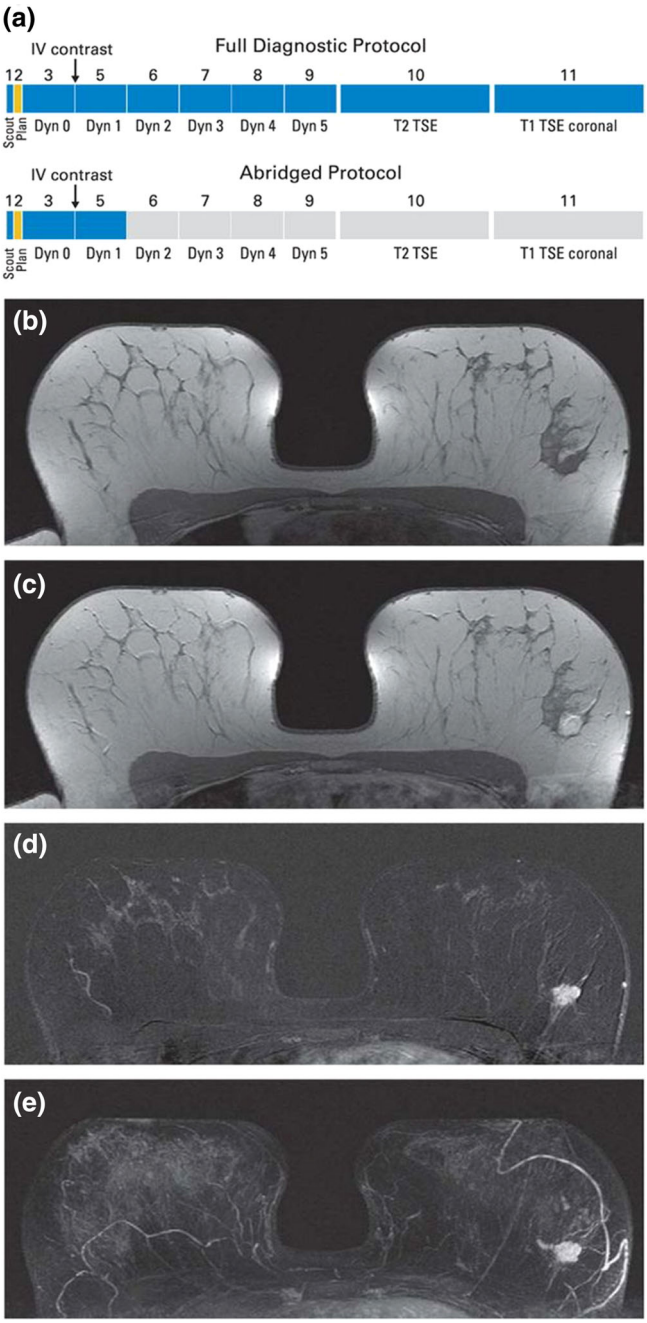

FIGURE 1: (A) Schematic presentation of full diagnostic and abbreviated protocols and **(B–E)** clinical example of calculation of first postcontrast subtracted (FAST) and maximum intensity projection (MIP) images in patient with left-sided breast cancer. (B) Midbreast section of baseline (precontrast) dynamic acquisition (A; Dyn 0); (C) corresponding section of first postcontrast dynamic acquisition (A; Dyn 1); (D) corresponding FAST image, generated by subtracting image (B) from image (C); and (E) MIP image, generated by fusing all FAST sections into single 3D-like projection image. Scout is automatic survey. Dyn refers to single dynamic acquisition consisting of image stack of 27 to 33 individual axial images; Dyn 0 is baseline dynamic acquisition, obtained before contrast agent injection, and Dyn 1 to Dyn 5 are five consecutive dynamic acquisitions obtained after contrast injection. IV, intravenous; TSE, turbo spin echo. Reprinted with permission from: Kuhl CK, Schrading S, Strobel K, et al. J Clin Oncol 2014;32:2304–2310.

with equivalent diagnostic accuracy for the abbreviated and full protocols, while evaluation of the MIP image alone missed one cancer.

The initial findings by Kuhl et al were supported by a study by Mango et al, who in 2015 reported the feasibility of an abbreviated protocol consisting of fat-saturated T_1-weighted precontrast, early postcontrast T_1, and subtraction MIP sequences.[38] All 100 cancers of known breast cancer patients were found by at least one of four readers, with a sensitivity of 96% for the first postcontrast image, 96% for the first postcontrast subtraction image, and 93% for the MIP image (Fig. 2). Both the Kuhl et al and Mango et al studies suggest that the MIP image alone is not sufficient for the detection of breast cancer or an accurate BI-RADS assessment; however, this might be accomplished using only the first postcontrast sequence. Similar to the Kuhl et al study, the Mango et al study yielded substantially decreased image acquisition and interpretation times of 10–15 minutes and 44 seconds, respectively.

Since these initial studies, numerous others have investigated the use of different abbreviated MRI protocols for breast cancer screening and the assessment of known cancer lesions. Moschetta et al found no significant differences in diagnostic accuracy between a full and an abbreviated protocol including STIR, T_2-weighted sequences, a precontrast, and single postcontrast T_1-weighted sequence.[36] Dogan et al investigated an abbreviated high-risk screening protocol consisting of T_2-weighted imaging and the Dixon sequence for DCE-MRI, yielding the same image quality equivalent to a separate full protocol.[26] Choi et al evaluated the usefulness of an abbreviated MRI protocol with fat-suppressed T_2-weighted imaging, pre- and postcontrast T_1-weighted images, and subtracted MIPs in 799 examinations for screening of 725 women with a history of breast cancer. In that study, 12 malignancies were detected, with five lesions visible on MRI alone.[25]

Whereas the above-mentioned studies included T_2-weighted or STIR sequences in their protocols, others solely relied on DCE-MRI. Petrillo et al investigated an abbreviated protocol including one precontrast T_1-weighted and the first postcontrast T_1-weighted series in 508 patients, yielding similar results with comparable diagnostic accuracy of the abbreviated and the full protocols.[32] Romeo et al used a protocol that included localizer, precontrast, and three timepoint postcontrast sequences to enable the assessment of the delayed enhancement. This abbreviated protocol yielded comparable results to a full diagnostic breast MRI protocol (area under the curve [AUC] 0.98 vs. 0.99; $P = 0.76$).[29]

A major advantage of breast MRI is that it is independent of breast density, which is a limiting factor of screening with mammography. In this context, Chen et al investigated an abbreviated protocol with T_1-weighted pre-, post-, and

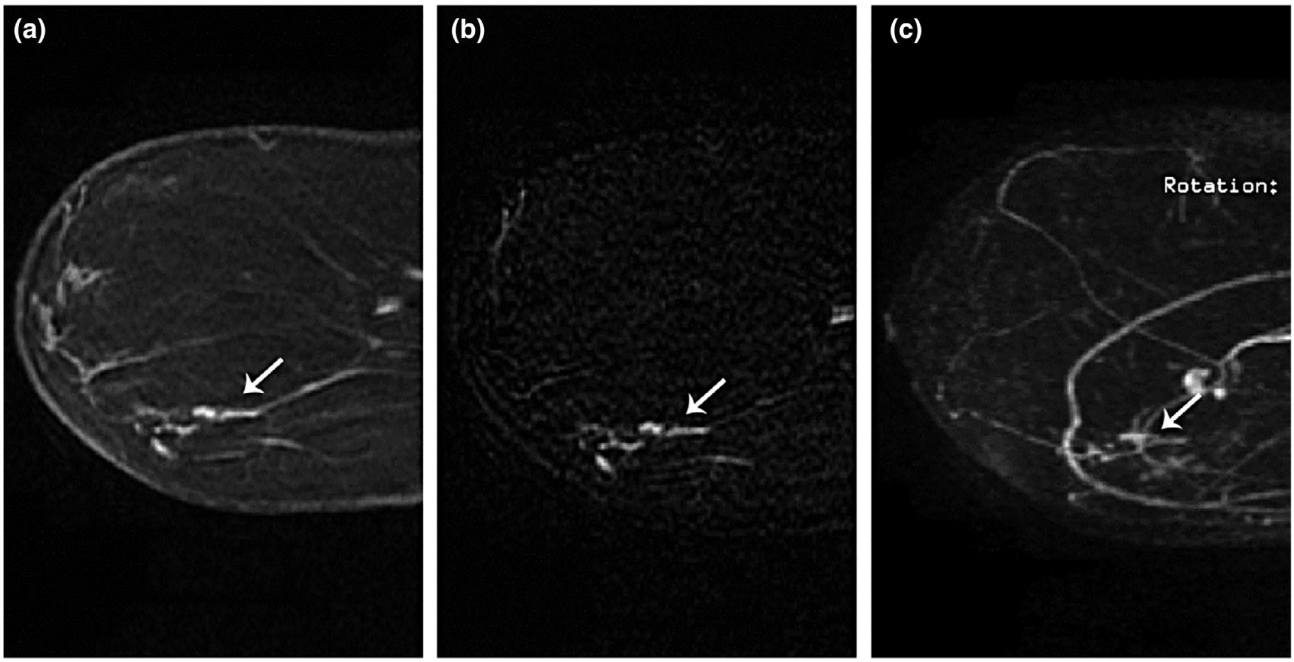

FIGURE 2: A 54-year-old female for high-risk screening. New linear nonmass enhancement in the lower outer left breast measuring 1.9 cm. MRI-guided core biopsy yielded DCIS with microinvasion. Cancer recognized by all four radiologists on reading of the abbreviated protocol. First postcontrast sequence (A), first postcontrast subtraction sequence **(B)** and subtraction maximum intensity projections (MIP) sequence **(C)**. Reprinted with permission from: Mango VL, Morris EA, Dershaw D, et al. Eur J Radiol 2015;84:65–70.

MIP images in 478 patients with dense breasts. There was no significant difference in cancer yield between the abbreviated and full diagnostic protocol.[31] Currently, the ECOG-ACRIN 1141 Trial,[57] "Comparison of Abbreviated Breast MRI and Digital Breast Tomosynthesis in Breast Cancer Screening," is ongoing. This prospective randomized phase II trial aims to compare an abbreviated breast MRI exam and digital breast tomosynthesis for detecting cancer in women with dense breasts. This trial was designed to investigate abbreviated breast MRI for the screening of average-risk women with dense breasts and thus the results are highly anticipated.

Given these different abbreviated MRI protocols, efforts have been made to identify the sequences that are necessary for a confident breast cancer diagnosis. Strahle et al used a full diagnostic protocol in 452 lesions to prospectively identify the most important sequences for breast MRI screening.[33] They concluded that T_2-weighted, T_1-weighted precontrast, first and late postcontrast images are necessary and enable a rapid breast cancer screening with a scan time of 7.5 minutes. Heacock et al compared three different protocols in 107 cancers and found that T_2-weighted imaging increased lesion conspicuity without altering the cancer detection rate.[24]

Recently, other aspects of using abbreviated breast MRI protocols have been investigated. In a recent study, Panigrahi et al[30] assessed the impact of an abbreviated protocol on the assigned BI-RADS assessment category. Comparison of a full diagnostic protocol to an abbreviated protocol in 1052 cases demonstrated that the full protocol resulted in a change in final BI-RADS assessments in only 3.4% of the cases.[30]

In the studies reviewed, the abbreviated protocols consisted of unenhanced and first contrast-enhanced T_1-weighted sequences, while some of them additionally included T_2-weighted, STIR, second contrast-enhanced, subtraction, and MIP images. The different studies and protocols are summarized in Table 1. While the time to interpret images was also substantially reduced using the abbreviated protocol in most studies,[34,36] only one study showed no difference in interpretation time between a full and an abbreviated protocol.[37] In almost all the studies reviewed, the short acquisition time and fast image interpretation of varying abbreviated protocols had no negative effect on diagnostic accuracy[20,36,38] (Figs. 3–5).

To date, the abbreviated breast MRI exam has been performed in eight different countries and in over 4500 women. A shared finding in almost all abbreviated MRI studies is that the cancers detected were mainly early-stage invasive cancers, with percentages ranging from 64–97%. The ductal carcinomas in situ (DCIS) detected with abbreviated MRI screening were predominately intermediate or high-grade DCIS.[20,22,24,26,29,30,32,34,35,38] This is in good agreement with a recent study by Sung et al, who found that in women at high breast cancer risk who underwent screening with both mammography and MRI, invasive cancers were more likely to be detected with MRI, while most cancers found with mammography were DCIS.[58] All these studies highlight that MRI using an abbreviated protocol is poised to be a supplemental screening tool designed to detect mammographically occult and biologically relevant breast cancer.[59]

TABLE 1. Abbreviated MRI Protocols Used in 21 Studies

Reference	Abbreviated Protocol 1	Abbreviated Protocol 2	Abbreviated Protocol 3
Platel et al 2014	Five standard and twenty ultrafast view-sharing contrast-enhanced T1-weighted images		
Kuhl et al 2014	Unenhanced T1-weighted imaging without fat saturation First contrast-enhanced T1-weighted imaging without fat saturation Subtraction MIP		
Mann et al 2014	Contrast-enhanced TWIST T1-weighted imaging		
Mango et al 2015	Unenhanced fat-saturated T1-weighted imaging First contrast-enhanced fat-saturated T1-weighted imaging Fat-saturated T1-weighted imaging Subtraction MIP		
Grimm et al 2015	Fat-saturated T2-weighted imaging Unenhanced fat-saturated T1-weighted imaging First contrast-enhanced fat-saturated T1-weighted imaging	Abbreviated 1 protocol + Second contrast-enhanced fat-saturated T1-weighted imaging	
Harvey et al 2016	Unenhanced fat-saturated T1-weighted imaging Contrast-enhanced fat-saturated T1-weighted imaging Subtraction MIP		
Heacock et al 2016	Unenhanced fat-saturated T1-weighted imaging First contrast-enhanced fat-saturated T1-weighted Subtraction No previous imaging	Abbreviated protocol 1 + With previous imaging	Abbreviated protocol 1 + With previous imaging + Fat-saturated T2-weighted imaging
Moschetta et al 2016	STIR Turbo spin-echo T2-weighted imaging Unenhanced THRIVE Intermediate contrast-enhanced THRIVE (3 min after gadolinium injection)		
Pineda et al 2016	Contrast-enhanced fat-saturated T1-weighted imaging with high spatial and temporal resolution		

TABLE 1. Continued

Reference	Abbreviated Protocol 1	Abbreviated Protocol 2	Abbreviated Protocol 3
Abe et al 2016	Eight high-temporal-resolution and four standard contrast-enhanced T1-weighted images		
Machida et al 2017	Unenhanced fat-saturated T1-weighted imaging First contrast-enhanced fat-saturated T1-weighted imaging		
Chen et al 2017	Subtraction MIP		
Strahle et al 2017	T2-weighted imaging Unenhanced fat-saturated T1-weighted imaging Early contrast-enhanced fat-saturated T1-weighted imaging Late contrast-enhanced fat-saturated T1-weighted imaging		
Petrillo et al 2017	Unenhanced fat-saturated T1-weighted imaging First contrast-enhanced fat-saturated T1-weighted imaging		
Panigrahi et al 2017	Unenhanced fat-saturated T1-weighted imaging First contrast-enhanced fat-saturated T1-weighted imaging Subtraction MIP		
Romeo et al 2017	Unenhanced fat-saturated T1-weighted imaging Contrast-enhanced fat-saturated T1-weighted imaging subtractions at 3 time points		
Oldrini et al 2017	MIP	Contrast-enhanced TRICKS acquisitions at 12 timepoints + MIP	Contrast-enhanced TRICKS acquisitions at 12 timepoints + Unenhanced fat-saturated T1-weighted imaging + T2-weighted imaging + MIP
Choi et al 2018	T2-weighted imaging Unenhanced fat-saturated T1-weighted imaging Contrast-enhanced fat-saturated T1-weighted imaging MIP		
	T2-weighted imaging		

TABLE 1. Continued

Reference	Abbreviated Protocol 1	Abbreviated Protocol 2	Abbreviated Protocol 3
Dogan et al 2018	Contrast-enhanced fat-saturated T1-weighted imaging		
Oldrini et al 2018	Unenhanced fat-saturated T1-weighted imaging First contrast-enhanced fat-saturated T1-weighted imaging Subtraction		
Jimenez et al 2018	Contrast-enhanced T1-weighted STELLR imaging		

Abbreviated protocols 2 and 3 were read by the same reader using the different additional sequences and/or available prior imaging.

Kinetic Information With High Temporal Resolution Protocols

The shortened acquisition time of abbreviated MRI protocols comes at the expense of kinetic information of breast tumors. However, the consensus is that kinetic information over time in addition to tumor morphology adds valuable information and increases specificity. Benign lesions typically show an initial slow or medium/delayed persistent enhancement, while an initial fast/delayed washout is highly indicative of malignancy. A full diagnostic protocol that includes several timepoints after contrast agent application would allow the semi-/quantitative assessment of tumor enhancement kinetics over time; however, an abbreviated MRI protocol that typically includes only one postcontrast scan would not allow such an assessment.

To overcome this limitation of abbreviated MRI protocols, several studies have explored the utility of shortened MRI protocols performed with imaging acceleration techniques.[60] Acceleration techniques decrease acquisition time while maintaining high spatial resolution.[61] Hence, high temporal resolution can be used for the extraction of kinetic information without a tradeoff in high spatial resolution and diagnostic confidence.

View-sharing is an important acceleration technique, where *k*-space periphery is undersampled, and data from different *k*-spaces are used to achieve high spatial resolution

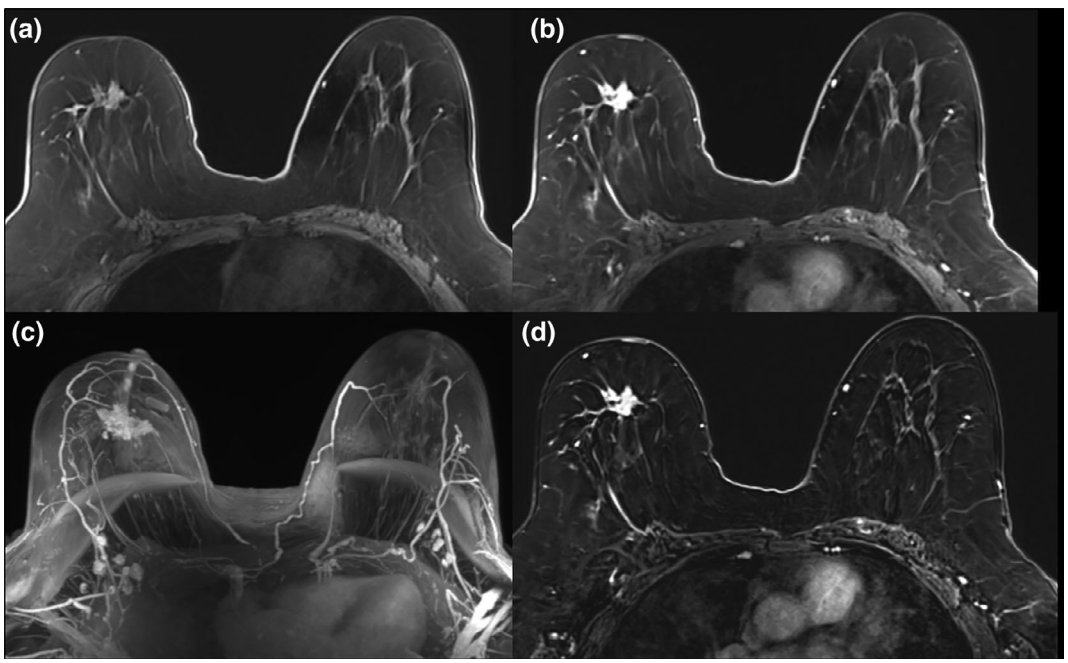

FIGURE 3: Invasive lobular carcinoma (ILC) in the right breast of a 59-year-old patient. The irregular, spiculated 3.5 cm mass (A) demonstrates heterogeneous contrast enhancement on early contrast-enhanced axial T_1W **(B)**, maximum intensity projections (MIP) **(C)**, and subtraction images axial T_1W postcontrast **(D)** and was accurately diagnosed with an abbreviated MRI protocol.

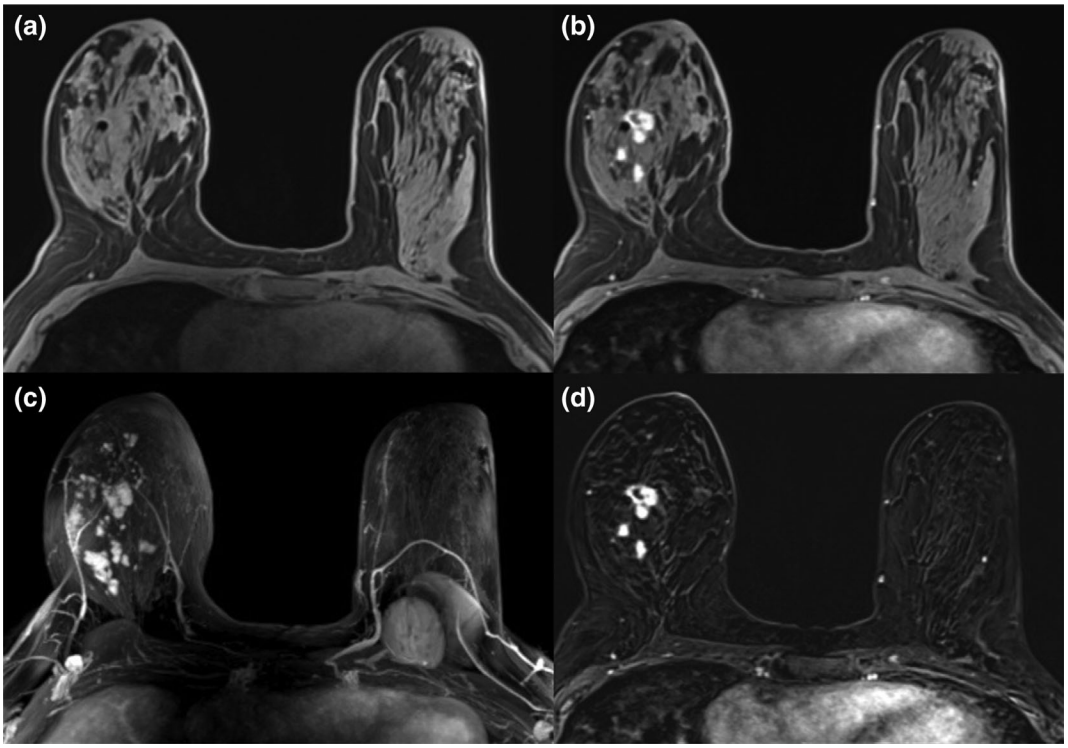

FIGURE 4: A 29-year-old patient with biopsy-proven breast cancer in the right breast. Abbreviated MRI of the breast including unenhanced (A), early contrast-enhanced axial T_1W **(B)**, maximum intensity projections (MIP) **(C)** and subtraction images axial T_1W postcontrast **(D)** was useful for the assessment of the true extent of disease, revealing multiple contrast-enhancing satellite lesions in the right breast.

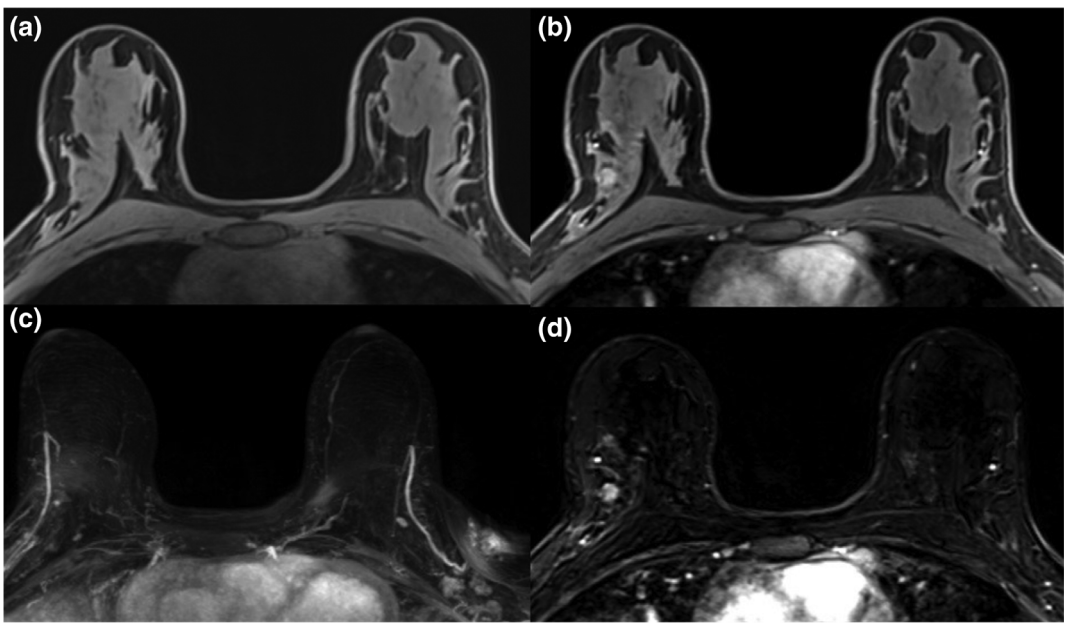

FIGURE 5: Fibroadenoma in the right breast in a 26-year-old patient with a BRCA2 gene mutation (A). On high-risk screening MRI there was a 0.9 cm mass lesion in the right breast, showing homogeneous contrast enhancement with a type I enhancement curve in the postcontrast axial T_1W **(B)** and subtraction images axial T_1W postcontrast **(D)**. This benign lesion was not depicted on maximum intensity projections (MIP) images **(C)**.

while contrast is measured in the center of *k*-space.[62] A commonly used view-sharing sequence for acquisition of both high temporal and spatial resolution imaging is time-resolved angiography with stochastic trajectory (TWIST).[63,64] Mann et al used a TWIST-based DCE-MRI protocol, comparing the diagnostic performance of the maximum slope of enhancement with a conventionally acquired kinetic curve.[41] Their protocol shortened imaging time while maintaining cancer yield and diagnostic accuracy, suggesting that delayed phase of the kinetic curve might not be needed for an

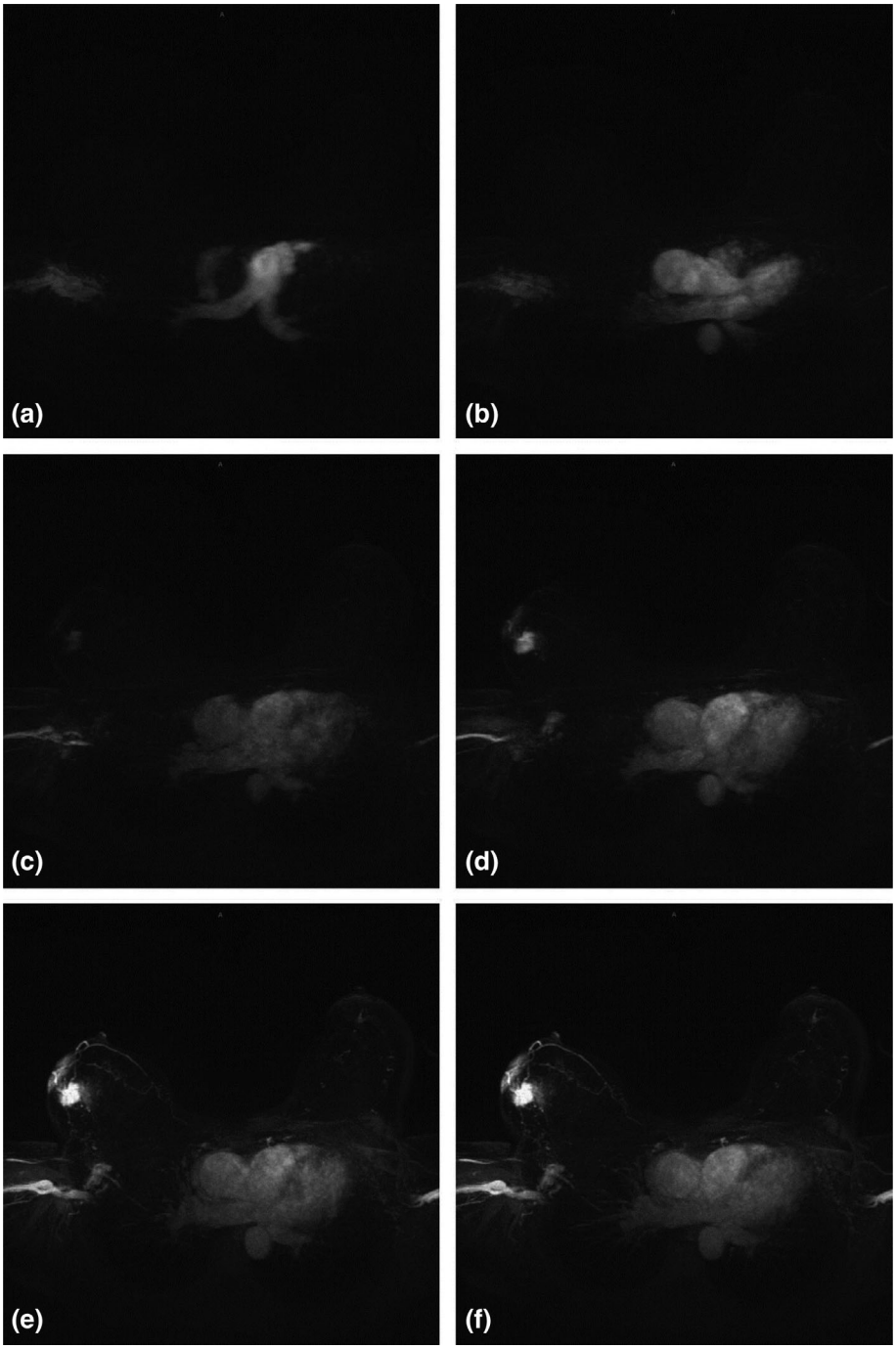

FIGURE 6: Selected stills (maximum intensity projections) from a movie of contrast inflow. A: Only the pulmonary artery enhances. **B**: The contrast has reached the aorta. **C**: The tumor in the right breast starts to enhance, just as the overlying infiltrated skin. **D**: The tumor stands out like a light bulb in a further empty breast. **E**: The draining veins become visible. **F**: Minimal normal glandular tissue enhancement is seen. Modified with permission from: Mann RM, Mus RD, van Zelst J, et al. Invest Radiol 2014;49:579–585.

accurate lesion detection and classification (Figs. 6–7). Platel et al found similar results when using a computer-aided diagnosis system.[40]

Pineda et al first explored a different acceleration technique using Fourier sampling and a high sensitivity-encoding (SENSE) acceleration factor.[39] They demonstrated that lesion conspicuity was highest on early images in the first minute after contrast administration, with significant differences in time of arrival between malignant and benign lesions. A follow-up study by Abe et al confirmed these initial results and demonstrated that fast MRI is at least equal in diagnostic performance compared with standard diagnostic MRI protocols.[42]

Most recently, Jimenez et al[21] developed a volumetric imaging technique with 0.8-mm isotropic resolution and 10-s/volume rate for breast cancer using parallel imaging and spatial compressed sensing. This approach allowed the assessment of lesion morphology and early-phase perfusion with a

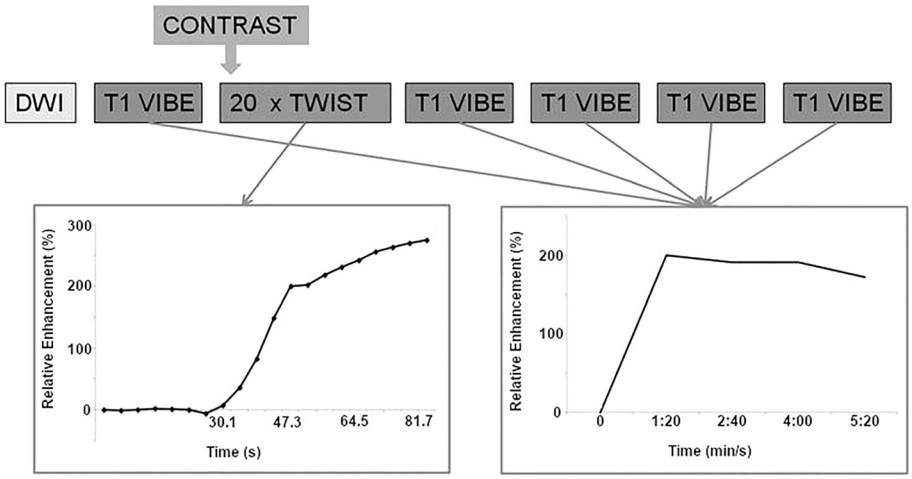

FIGURE 7: Schematic drawing of the breast MRI scan protocol: The TWIST acquisitions allow evaluation of the contrast inflow in the lesion, whereas the VIBE acquisitions are used for three-timepoint analysis, creating the classic contrast enhancement versus time curve. Modified with permission from: Mann RM, Mus RD, van Zelst J, et al. Invest Radiol 2014;49:579–585.

total scan time of only 6 minutes. The authors conclude that upon further validation, this technique may translate to high-performance, rapid breast cancer screening with MRI.[21]

Oldrini et al evaluated time-resolved imaging of contrast kinetics (TRICKS) acquisitions compared with an abbreviated as well as a full diagnostic protocol.[23] The authors achieved an improved specificity when TRICKS acquisitions were added to the abbreviated protocol, outperforming the full protocol.

In summary, the results of these studies indicate that even with abbreviated breast MRI protocols, the necessary kinetic information for an accurate breast cancer diagnosis can be provided along with morphologic information.

Beyond Contrast

Due to its excellent sensitivity, DCE-MRI is currently the backbone of any given breast MRI protocol. Most recently, it has been demonstrated that the administration of gadolinium-based contrast agents (GBCAs) can cause MRI signal changes in the deep nuclei of the brain. While some linear contrast agents seem to cause greater MRI signal changes than some macrocyclic GBCAs, deposition of gadolinium has nevertheless been observed for macrocyclic GBCAs.[65–73] To date, the clinical significance of the brain retention of GBCAs is unknown, and there is no scientific evidence of adverse clinical effect. Nevertheless, the recent controversy about the safety of GBCAs has sparked the recommendation to use GBCAs only when essential diagnostic information cannot be obtained with unenhanced scans.[66,74] This is particularly relevant for the field of breast imaging where healthy women are screened for breast cancer with DCE-MRI. Therefore, there are considerable efforts to develop unenhanced MRI techniques with equal sensitivity for breast MRI screening.

Among all investigated unenhanced MRI techniques, diffusion-weighted imaging (DWI) has currently emerged as the most robust and valuable. DWI using apparent diffusion coefficient (ADC) mapping is reported to have a sensitivity of up to 96% for breast cancer detection and a specificity of up to 100% for breast tumor characterization.[75–77] Given the fact that DWI is robust, reliable, and fast to perform, with scan times usually ranging from 2–3 minutes, the use of DWI for abbreviated unenhanced screening is of interest.

Several authors have investigated abbreviated unenhanced protocols with different combinations of T_1-weighted and/or T_2-weighted with either DWI or DWI with background suppression, with encouraging results.[64,78–83] Shin et al investigated an abbreviated protocol using either an unenhanced protocol including high b-value DWI and T_1-weighted imaging or an enhanced protocol including early DCE-MRI sequences in 129 lesions; both abbreviated protocols achieved similar detection rates and diagnostic accuracy.[80] Baltzer et al[84] compared a DWI protocol with a DCE-MRI and T_2-weighted imaging protocol; both protocols achieved similar results with high diagnostic performance and interreader agreement (Fig. 8). Bickelhaupt et al[83] compared an unenhanced diagnostic abbreviated MRI protocol (consisting of maximum intensity projections from DWI with background suppression and unenhanced morphologic sequences with an acquisition time of less than 7 minutes) with an abbreviated DCE-MRI protocol as well as a full diagnostic MRI protocol to predict the likelihood of malignancy in patients with a suspicious finding on screening mammography. In that study, the abbreviated unenhanced MRI protocol was able to exclude malignancy in these patients with an negative predictive value of 0.92.[83] In summary, in all these studies, except for one study,[79] the sensitivity of abbreviated unenhanced MRI was equal[78] or superior to mammography.[64,80–83]

While these results are encouraging and highlight the potential of DWI as a promising MRI technique for an abbreviated unenhanced protocol, a recent study comparing DCE-MRI, DWI as a stand-alone parameter for breast cancer

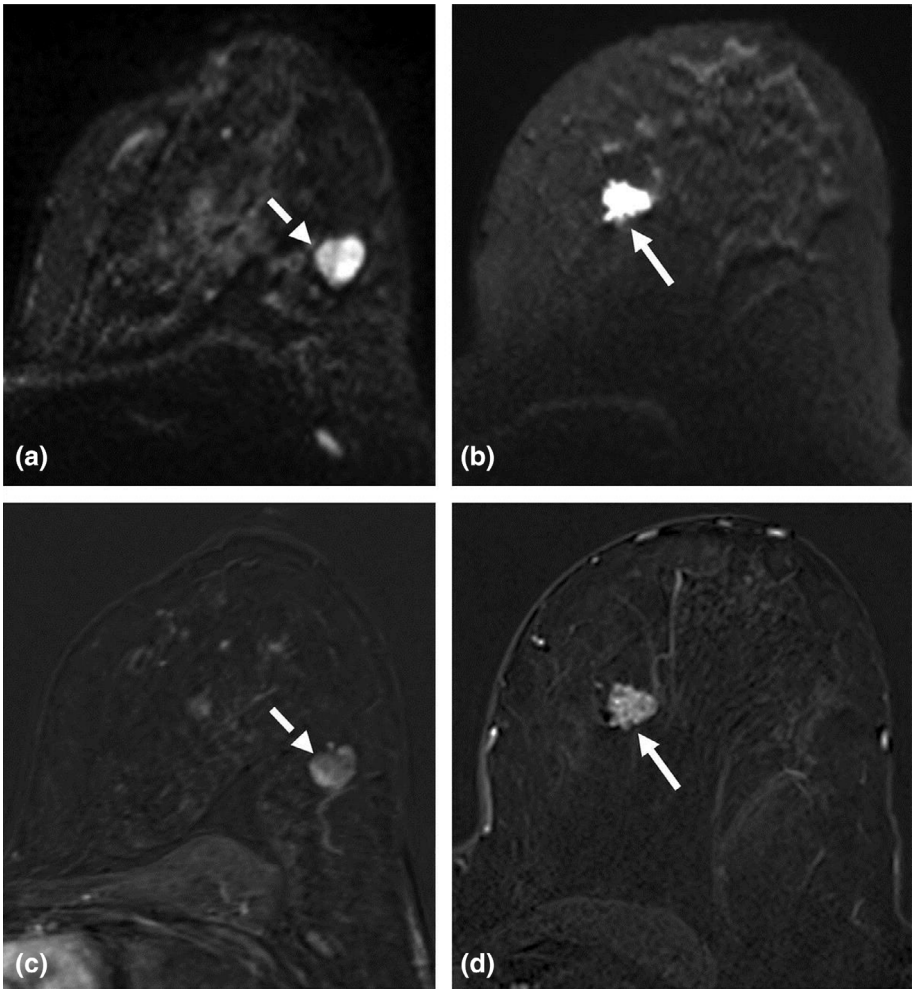

FIGURE 8: Comparison of morphologic assessment on NC-MRI and CE-MRI. (A) A circumscribed round lesion on the b850 s/mm^2 image (dashed arrow), while **(B)** visualizes a noncircumscribed, rather spiculated lesion on the b850 s/mm^2 image (arrow). The lesion from panel A appears with circumscribed margins on the early contrast-enhanced subtraction (**C**, dashed arrow) and was histologically proven as a fibroadenoma, while the lesion from panel B appears noncircumscribed with heterogeneous internal structure and a feeding vessel on the early contrast-enhanced subtraction (**D**, arrow) and corresponds to an invasive ductal carcinoma G2. Reprinted with permission from: Baltzer PAT, Bickel H, Spick C, et al. Invest Radiol 2018;53:229–235.

detection, and combined DCE-MRI and DWI demonstrated that DCE-MRI remains the most sensitive protocol for breast cancer detection. A current limitation of DWI is that its sensitivity is limited in lesions smaller in lesions ≤12 mm or presenting as diffuse nonmass enhancement[63] (Fig. 9). However, research to improve the spatial resolution of DWI is ongoing. Hence, it can be expected that further advances are possible to overcome its current limitations. Several studies have demonstrated that the combination of DCE-MRI and DWI maintains a high sensitivity, increases specificity, and maximizes diagnostic accuracy[44] (Fig. 10); therefore, it seems that there is also potential for the application of abbreviated MRI protocols with combined DCE-MRI and DWI in breast cancer screening.

Abbreviated MRI as a Valuable Initiative

The abbreviated MRI exam has been embraced in the radiology community as an important and valuable initiative. Current studies focusing on the role of MRI in screening and surveillance have developed specialized protocols that are often abbreviated with applications in the prostate and liver.[85–92] Variable imaging protocols have been used and in general show a similar diagnostic performance compared with the full protocol for the detection of occult malignancies. Other novel applications include using abbreviated MRI in the pediatric population to decrease the duration of necessary sedation, and as a rapid and accurate imaging tool in the musculoskeletal setting to detect fractures and increase patient throughput in an emergency setting.[93–95]

The above studies reflect the increasing scrutiny on the disproportionate contribution of radiology to the rising overall healthcare expenditures. As a result, value-based healthcare is the new paradigm that has quickly replaced the fee-for-service model.[96–101] Healthcare policy makers have focused on curbing the use of advanced imaging examinations, especially computed tomography (CT) and MRI,

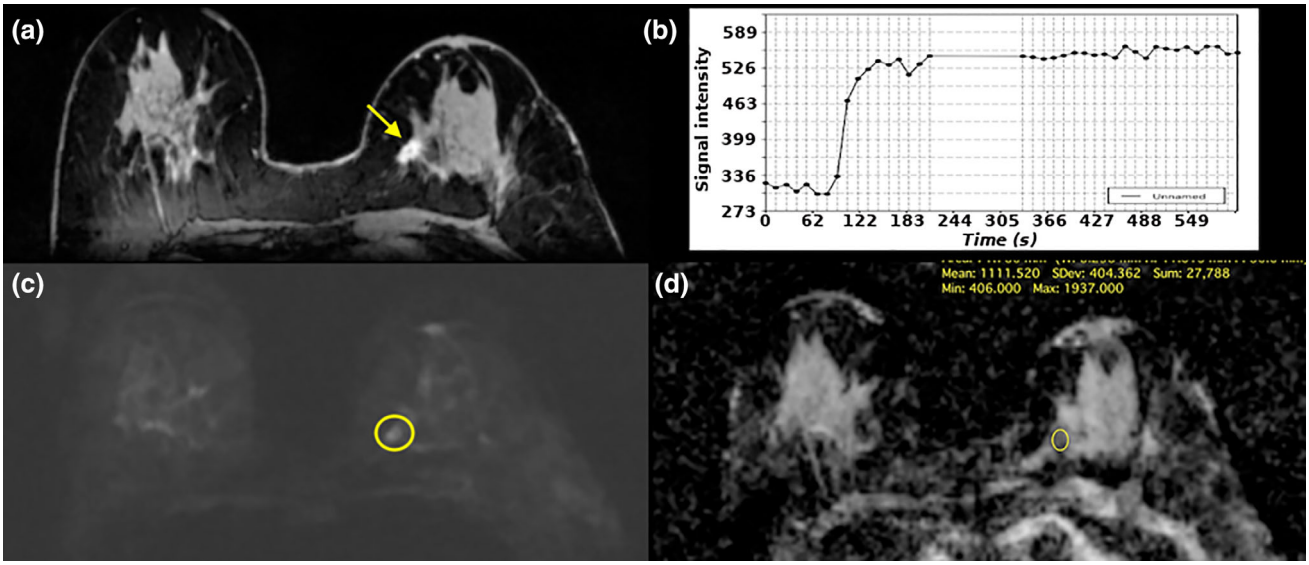

FIGURE 9: Invasive ductal carcinoma (IDC) G1 in the left breast medial in a 71-year-old woman. (A) On DCE-MRI there is a 10mm irregular-shaped and marginated lesion (arrow) with **(B)** an initial fast/plateau enhancement (II); DCE-MRI findings were classified as suspicious for malignancy (BI-RADS 4). DWI was false negative as none of the readers called this lesion on DWI alone. However, when read as mpMRI combining DCE-MRI and DWI, readers identified a **(C)** hyperintense correlate (circle) with **(D)** ADC values measuring 1.111 × 10^{-3} mm^2/s, which further confirmed malignancy.

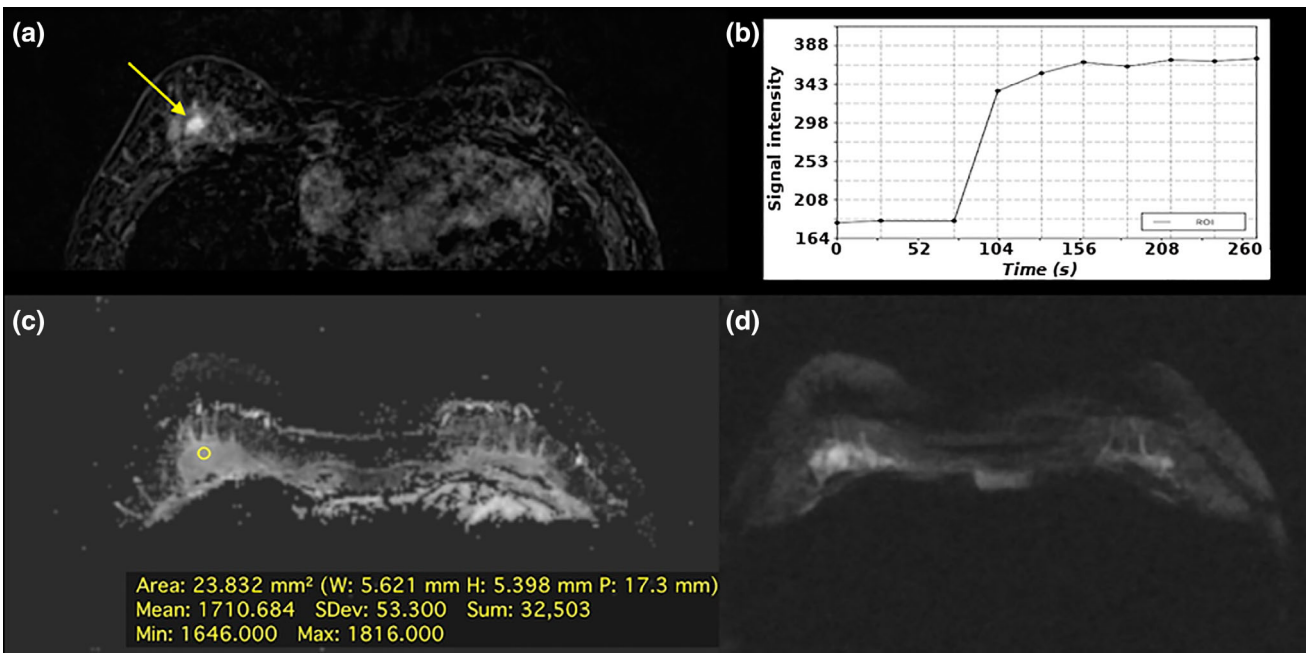

FIGURE 10: Fibroadenoma in a 39-year-old woman, central in the right breast: (A) The irregular-shaped and partially irregularly marginated 7 mm mass demonstrates **(B)** an initial medium/persistent (II) slightly homogenous contrast enhancement and was classified as suspicious (BI-RADS 4). **(C)** On DWI there is no focal restricted diffusivity and **(D)** no decreased ADC values (1.710 × 10^{-3} mm^2/s). DCE-MRI and DWI were discordant. According to the BI-RADS-adapted reading algorithm, the BI-RADS assessment category assigned based on DCE-MRI was overruled. Multiparametric MRI correctly classified the mass as benign and would have obviated an unnecessary breast biopsy.

while promoting the quality and appropriateness of imaging. These policy changes have led to a variety of new metrics that are being imposed on radiology providers. Further, clinical decision support tools have been introduced, many of which focus on limiting the use of these advanced imaging tools.

An important cornerstone of value-based healthcare is that value is defined as the patient's outcome over costs.[101] A correct diagnosis is the first outcome that matters to patients, and new metrics have been developed to measure the radiologist's impact on patient outcomes. These metrics will measure a radiologist's contribution to reducing costs and improving

patient outcomes with the intention of making reimbursement commensurate with adherence to these metrics.[96] The concept of a fast, abbreviated MRI exam is therefore appealing, given its high diagnostic accuracy coupled with the possibility of a marked reduction in the cost of an MRI examination. In addition, abbreviated MRI exams will enable higher volume patient throughput, thereby generating more revenue and being more cost-effective.

Multiple investigators are evaluating if these rapid MRI exams are cost-effective enough to provide the initial diagnosis.[20,22,25,27–31,33–38,83,85,86,93] In breast imaging, one of the goals is to evaluate if an abbreviated breast MRI may be a first-line exam and compete with other imaging exams such as 2D screening mammograms, digital breast tomosynthesis, and whole breast screening ultrasound exam. Current studies are limited by the heterogeneous imaging protocol and variable inclusion criteria for the patients. Most studies have shown a similar diagnostic accuracy to a full MRI exam. Will it be acceptable if an abbreviated MR exam is not as thorough as a standard MR exam, but good enough to triage patients more cost effectively? This topic is currently subject to intense research, aided by new technologies such as synthetic MRI reconstruction, MR fingerprinting, and the use of deep-learning tools for MR reconstruction.

Challenges and Outlook

An unresolved issue is the reimbursement for an abbreviated breast MRI exam and the way it will be implemented in the clinical workflow. This limitation applies to abbreviated protocols that are being evaluated for all organ systems, including the breasts. To our knowledge, the cost of an abbreviated MRI exam has yet to be determined because such an exam is currently being evaluated with respect to feasibility and/or is being validated by other studies. Therefore, important issues such as the length of the abbreviated MRI exam and whether a gadolinium contrast agent is necessary need to be resolved before the issue of the cost of the exam may be addressed. From an operations viewpoint, it is clear that "scan time" is not equivalent to "table time." This information is critical to estimating the price point for an abbreviated MR exam. Operational improvements to maximize patient throughput haven't been explored, since abbreviated exams are mainly performed in the research setting. Novel ideas, such as multihead MRI scanners, will improve the efficiencies of the abbreviated MRI exam.

Paving the way to address the issue of cost is the ECOG-ACRIN 1141 Trial[57] to compare abbreviated breast MRI and digital breast tomosynthesis for the detection of breast cancer in average-risk women with dense breasts. The primary aim of the study is to compare the invasive cancer detection rates of both exams. One of the secondary aims of this multicenter study is to perform a comparative cost analysis of both exams. Although the hypothetical cost of an abbreviated breast MRI is still being explored, a reasonable number would be a low-cost exam that is competitive with other breast imaging screening exams such as mammography, digital breast tomosynthesis, and screening breast ultrasound.

Although results from previous studies investigating abbreviated MRI protocols are promising, they might not be generalizable to a broad population. To date, these protocols have only been investigated for breast cancer screening and still have to be evaluated for their value in the diagnostic setting or for neoadjuvant chemotherapy response assessment. In addition, the calculated time for these protocols may not reflect the entire time of the examination, as there are other workflow considerations such as setup, room turnover, safety screening, and IV placement that must be considered. However, with training of personnel and work-flow optimization an abbreviated MRI examination will still be substantially shorter than one with a full protocol and allow higher volume patient throughput. Another aspect that needs to be considered is that, although in the study setting reading times can be substantially shortened, it has to be seen where this will translate into clinical reality where an MRI interpretation may also include reviewing patient's history and priors.

Abbreviated MRI protocols still need refinement, standardization across sites, and validation by prospective multicenter trials before they can be implemented into clinical routine. Nevertheless, it can be expected that abbreviated MRI protocols will play an important role in breast imaging in the future.

Conclusion

MRI of the breast is undisputedly the most sensitive test for breast cancer detection and outperforms conventional imaging with mammography, tomosynthesis, and ultrasound, yet to date is only routinely implemented in the screening of women at an increased risk of breast cancer. Its widespread use as a screening tool for women at average risk of breast cancer is currently limited by its relatively high costs, long examination, and reading times. Recently, abbreviated DCE-MRI protocols have been introduced that substantially shorten image acquisition and interpretation time, allow higher volume patient throughput, thus being more cost-effective, while maintaining a high diagnostic accuracy. With respect to the controversy to address concerns that DCE-MRI may cause unnecessary costly breast biopsies, unenhanced MRI parameters such as DWI are under investigation to be added to abbreviated MRI protocols to mitigate this limitation. Although further larger-scale studies and rigorous standardization is necessary, the initial results suggest that it seems feasible to offer a cost-effective screening breast DCE-MRI to a broader population.

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