What’s Hot in Breast MRI

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Abstract
Several articles in the literature have demonstrated a promising role for breast MRI techniques that are more economic in total exam time than others when used as supplement to mammography for detection and diagnosis of breast cancer. There are many technical factors that must be considered in the shortened breast MRI protocols to cut down time of standard ones, including using optimal fat suppression, gadolinium-chelates intravascular contrast administrations for dynamic imaging with post processing subtractions and maximum intensity projections (MIP) high spatial and temporal resolution among others. Multiparametric breast MRI that includes both gadolinium-dependent, i.e., dynamic contrast-enhanced (DCE-MRI) and gadolinium-free techniques, i.e., diffusion-weighted/diffusion-tensor magnetic resonance imaging (DWI/DTI) are shown by several investigators that can provide extremely high sensitivity and specificity for detection of breast cancer. This article provides an overview of the proven indications for breast MRI including breast cancer screening for higher than average risk, determining chemotherapy induced tumor response, detecting residual tumor after incomplete surgical excision, detecting occult cancer in patients presenting with axillary node metastasis, detecting residual tumor after incomplete breast cancer surgical excision, detecting cancer when results of conventional imaging are equivocal, as well patients suspicious of having breast implant rupture. Despite having the highest sensitivity for breast cancer detection, there are pitfalls, however, secondary to false positive and false negative contrast enhancement and contrast-free MRI techniques. Awareness of the strengths and limitations of different approaches to obtain state of the art MR images of the breast will facilitate the work-up of patients with suspicious breast lesions.

Keywords
breast, magnetic resonance imaging, breast cancer

Breast magnetic resonance imaging (MRI) has been subject to significant quality improvement since surface coils were used to provide higher spatial resolution. Dedicated breast coils are mandatory for state-of-the-art exams. Intravenous gadolinium-chelates based contrast agents (GBCA) are used to detect angiogenesis and form the basis of dynamic-contrast enhanced (DCE)-MRI. Unfortunately, the need for i.v. GBCA results in brain, bone and soft tissue retention in patients with a normal kidney function, which is accentuated in patients with poor renal function. It is unknown whether these GBCA deposits are harmful or can lead to adverse health effects. Studies have shown that the stability of GBCA is associated with the degree of retention. For this reason, linear nonionic contrasts retain more gadolinium than linear ionic, and linear ionic more than macrocyclic contrasts. A recent trend to utilize gadolinium-free MRI techniques in clinical scenarios where use of GBCA is a challenge, like pregnancy, severe contrast allergies, and lactational status rely on Diffusion-(GBCA-free)-MRI techniques (DWI/DTI-MRI) that are based on the intrinsic cellular contrast.

Indications for Breast MRI
A summary of the current indications for Breast MRI is presented in the Table 1.

Diagnostic Breast MRI for Silicone Implant Evaluation
Breast MRI shown to be superior in detecting implant rupture with sensitivity and specificity ranging from 78-99% compared to ultrasound and mammography of respectively, 59-81% and 28-89%. Classical MRI findings for intracapsular rupture include the linguine and keyhole signs. The MRI protocol for detection of silicone leak is different.

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from the protocol for breast cancer. It is a GBCA-free breast MRI using protocols mainly based on long relaxation time and selective silicone-specific sequences that allow separation of the water and silicone in the presence of inhomogeneous magnetic fields and do not require diffusion/DCE MRI techniques. Hence, it is important for the referring physician to clearly define the purpose of the breast MRI if the concern is a silicone leak. For the increasingly recognized risk of Breast Implant-associated Anaplastic Large Cell Lymphoma (BIA-ALCL), a T-cell lymphoma typically associated with textured implants occurring at a median of 10-years after inclusion, features of peri-implant effusion and less frequently masses may be image detected.55 For clinically suspected BIA-ALCL, breast ultrasound is elected the first imaging test of choice.36

**Diagnostic Breast MRI for Carcinoma of Unknown Primary**

The American Society of Breast Surgeons 2017 guideline supports the use of breast MRI to search for occult breast cancer in patients with Paget’s disease of the nipple when clinical examination and conventional breast imaging fail to detect the primary breast cancer.37 Occult breast carcinoma may present with axillary lymphadenopathy that is histologically consistent with metastatic breast cancer (Figure 2). Less than 2% of patients present with clinically palpable axillary nodes and negative mammography/breast ultrasound. In such a clinical scenario, breast DCE-MRI can detect 75% of the initially occult primary breast carcinoma in the conventional breast imaging.38,39 Patients with a negative MRI who underwent breast conservation treatment instead of mastectomy had 96% breast cancer-free survival in a multicenter study with a small risk of ipsilateral recurrence.40

**Diagnostic Breast MRI for Preoperative Assessment of Breast Cancer**

The initial studies have shown that breast DCE-MRI can detect additional cancer (not identified on mammography/or ultrasound) in up to 33% of patients with newly diagnosed carcinoma.41-43 Breast MRI for evaluation of extent of disease, as a routine test, remains controversial among surgeons.37 It is unclear if MRI improves surgical outcomes, impacts survival or is cost effective.44 A multicentric randomized controlled trial (RCT) found surgical re-exCISIONs to be significantly lower, 5% vs 15% (p < 0.0001) with MRI.45 A Canadian population-based study demonstrated that just 14.8% of breast cancer patients treated 2003-2012 received pre-operative breast MRI. This test increased across all cancer stages by 8-fold, from 3% to 24% (p < 0.001).46 For suspected multicentric or contralateral disease, needle biopsy is required before surgical management to avoid unnecessary surgery for lesions that could be proven benign in up to 8%.47 For local staging, MRI is highly accurate in suspected pectoral (Figure 3) muscle invasion and may also help to assess nipple to tumor distance providing useful information about the ability to perform nipple sparing mastectomy if >1 cm from the nipple.48 Overall, breast MRI is quite useful in patients in whom the disease extent is uncertain from physical exam, mammography/ultrasound and several breast surgeons rely upon this imaging method for tailored surgical plan.49,50 The best established indications for preoperative MRI are for patients with dense breasts, those with invasive lobular carcinoma, or for those younger than 50 years of age.

**Diagnostic Breast MRI Related to Neoadjuvant Therapy (NAT)**

Breast MRI can be done before starting the pre surgical treatment with a wide variety of drugs that are indicated based on molecular pathology.51 The overall survival and disease progression in patients receiving neoadjuvant versus adjuvant chemotherapy are not considerably different,52 however women receiving NAT are more likely to be treated with breast conservation. This may be related to the substantial role that breast MRI plays in detecting suspicious lesions and providing accurate cancer mapping. Breast MRI has the capacity to provide

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**Table 1. Indications for Breast Magnetic Resonance Imaging (MRI) Associated to the MRI Protocol.**

| Clinical scenario                                      | DCE-MRI | DWI/DTI-MRI | Dedicated silicone |
|-------------------------------------------------------|---------|-------------|------------------|
| Silicone breast implant integrity evaluation          | Not required | Not required | Appropriate       |
| Screening for breast implant associated anaplastic large cell lymphoma staging | Not required | Not required | Appropriate       |
| Breast implant associated anaplastic large cell lymphoma staging | Appropriate | Appropriate* | Not required      |
| Screening for carcinoma of unknown primary with axillary metastasis | Appropriate | Appropriate* | Not required      |
| Surgical planning of a newly diagnosed breast cancer   | Appropriate | Not required | Not required      |
| Evaluation before, during or after breast cancer neoadjuvant therapy | Appropriate | Not required | Not required      |
| Evaluation of residual disease after breast cancer surgery | Appropriate | Not required | Not required      |
| Evaluation of recurrent malignancy after breast cancer treatment | Appropriate | Not required | Not required      |
| Pathologic nipple discharge                           | Appropriate | Not required | Not required      |
| Organized breast cancer screening                      | Appropriate | Not required | Not required      |
| Opportunistic breast cancer screening                  | Appropriate | Not required | Not required      |
| Inconclusive findings on non-MRI breast imaging tests  | Appropriate | Not required | Not required      |

Abbreviations: DCE-MRI = dynamic contrast-enhanced MRI; DWI/DTI = diffusion MR, either diffusion-weighted or diffusion-tensor.

* Not performed as stand-alone method.
** If the inconclusive findings are related to determine the integrity of silicone breast implant(s).
information on responders versus non-responders to NAT and to detect residual disease (Figure 4). Breast MRI is more accurate than clinical exam, mammography/sonography to correctly identify the presence of residual tumor in 92% of cases and to correctly identify the imaging findings of a pathologic complete response (pCR) in 90% of cases.\(^{55-57}\)

### Diagnostic Breast MRI for Postoperative Assessment

In patients where there is a close or positive surgical margin, MRI can be used to detect unsuspected multicentric or multifocal disease at the current threshold of 5 mm or higher. However, MRI may have difficulties in differentiating postsurgical change from residual cancer with a very low negative predictive value (45%) when there is associated enhancement of the surgical cavity.\(^{58-60}\)

### Diagnostic Problem-Solving Breast MRI

Breast MRI is extremely useful if there is no enhancement as the negative predictive value (NPV) is close to 100%.\(^{61-63}\) Used when mammography or sonography is not sufficient, e.g. questionable architectural distortions; nipple discharge with inconclusive findings; suspicious lesions seen in a single view digital mammography/digital breast tomosynthesis or even when equivocal changes at site of previous surgery (Figure 5) are noted. If inconclusive sonographic findings with a clinical suspicion of BIA-ALCL, DCE (with or without DWI/DTI)-MRI is indicated to assess for peri-implant effusion or mass.\(^{36,64}\) Organizing an MRI in cases where there is a palpable concern and an imaging correlate in order to substitute the need of the breast tissue histological diagnosis is not appropriate. If there is a clinical focal palpable concern, the appropriate choice imaging test is sonography plus or minus diagnostic mammography and based on the imaging descriptors, it could be likely benign (BI-RADS 3) or suspicious/highly suspicious (BI-RADS 4/5) and biopsied to establish the histological diagnosis and appropriate management. MRI should not replace the need for tissue biopsy.

### Breast MRI Screening for Early Breast Cancer(s) Detection

Screening breast MRI may apply to the evaluation of the contralateral breast in preoperative or pre-NAT evaluation in patients with breast cancer, and may be identified in 3-10%, depending on tumor histology and other risk factors. Breast MRI has become an essential screening modality for women at high-risk for breast cancer, particularly those with genetic mutations that markedly increase their risk of developing a breast cancer, such as BRCA 1/2 gene carriers\(^{65}\) or women with a very strong family history of breast and or ovarian cancer particularly in their first degree's relatives, women who have received chest irradiation for diseases during childhood, Hodgkin's lymphoma, and women with a lifetime risk of breast cancer >20-25%, as estimated by multiple risk assessment models. More recently, MRI has been recommended for higher than average risk women, including women with dense breasts (Figure 6), which is an independent risk factor for breast cancer.\(^{66}\) In the high-risk male population screening with breast MRI is not frequently used.\(^{67}\)

No RCT studies are available to prove the efficacy of screening breast MRI in the general population, however based on that 1 in 8 Canadian women will develop breast cancer during their lifetime and 1 in 33 will die from it,\(^{68}\) together with the scientific knowledge that of 9 cancers in 9 asymptomatic women will be all detected by MRI and 3 of the 9 cancers...
will be detected by mammography or sonography, it makes sense to develop strategies to make available for breast MRI to the general population.

The performance indicators of breast cancer screening using DCE-MRI show a wide range in published results, e.g., average sensitivity 91-98%; specificity 78-99%; NPV over 95%; positive predictive value (PPV) 53-75% that are mainly due to the radiologists’ learning curve and various MRI protocols and scanners. The ACR benchmarks for screening MRI are sensitivity >80% and specificity >85-90% with PPV3 (for biopsy performed) of 20-50% and cancer detection rates of 20-30 per 1000. It is essential to audit outcomes and the false positives on DCE-MRI, given the overlap of benign and malignant enhancing lesions that must undergo proper diagnostic work up. A RCT of 40,373 women with dense breasts undergoing supplemental breast cancer screening with MRI found a false positive rate of 7.98%. There are also false negative DCE-MRI cases e.g. invasive lobular carcinoma and low-grade DCIS which may not be detected because of the lack of post-GBCA enhancement. One study demonstrated that almost one-third of the false negative DCE-MRI were missed cancers while another third was misinterpreted. Double reading for screening breast MRI, radiologists’ audits and understanding the cognitive processes and unconscious biases are required to avoid human errors and decrease the number of unintentional missed breast cancers.

**What Makes MRI Detect Breast Cancer?**

The MRI key principle in detecting breast cancer relies upon the evaluation of the tumor angiogenesis or the development of new blood vessels/capillaries in tumors demonstrating that a primary cancer cannot grow above 1-2 mm without new vessels. The secondary cancer (metastasis) genesis involves not only angiogenesis but angiogenesis and lymphangiogenesis. The analysis of the physiological model of GBCA distribution in the breast considers the body extracellular volume, the plasma concentration of GBCA and the breast tissue contrast uptake that is regulated by the influx transcapillary transfer constant (flow and capillary permeability times capillary surface-area) and the efflux transcapillary transfer constant (which is a ratio of the extracellular volume fraction. The breast MRI curve of enhancement with wash-in and wash-out measurements is evaluated in a timeline and must have at least 3 points (preselected based on the model parameters of DCE and the MRI protocol) in order to be created. The curve of enhancement is a visual tool for the breast radiologist that represents the physiological features of cancer (showing wash-in phase-type 3 curve and fast rate of enhancement) versus benign (having mostly persistent wash-in phase-type 1 curve and slow rate of enhancement), when the transcapillary transfer constant is calibrated adequately in the many commercially available breast MRI software.
There has been a growing interest in the investigation of modified breast MRI protocols for cancer detection, from techniques that are completely GBCA-free like DTI,\textsuperscript{84} to the distinct sequences that focus mainly in the transcapillary GBCA transfer in the breast lesions requiring re-engineering of older MRI sequences in breast MR imaging\textsuperscript{85} in order to achieve high temporal resolution that became feasible in light of technical MR hardware improvements such as "Ultrafast MRI."
Figure 4. Invasive ductal carcinoma, grade 3, ER positive, PR positive, HER2-neu negative before starting the neoadjuvant chemotherapy with multiparametric diagnostic breast MRI showing a large enhancing cancer in the left breast on (A) the axial maximum intensity projection (MIP) images during the 2nd minute post gadolinium-based contrast agent, (B) and (C) are the same location slice taken in the upper breast showing the clumped internal non mass enhancement pattern during the 2nd minute post contrast of the dynamic contrast enhancement (DCE)-MRI and the color coded lambda-1 mapping of diffusion tensor MRI. The same patient underwent another multiparametric diagnostic breast MRI after receiving the 6 cycles of 21 days of chemotherapy with 3 drugs (fluoracil, epirubicin, and cyclophosphamide, called FEC) on day 1 of the first 3 cycles and with another drug (docetaxel, called D) on day 1 of the 3 last cycles (FEC-D). The residual post contrast enhancement on DCE-MRI was reported as 10 cm without significant internal response based on the RECIST criteria where (D) and (E) show, respectively, MIP and T1-weighted with fat suppression 3D-gradient echo in the 2nd minute and (F) shows the residual cancer demonstrated by DTI-MRI measuring 6 mm in the lambda-1 overlaid over T1-weighted image without fat suppression, indicating partial response. Same slice location corresponding to (F). The pathology results show overall cellularity of 5% within a 29 × 25 mm tumor bed of a residual invasive ductal carcinoma of no special type (NST) measuring 6 × 3 × 3 mm, Residual Cancer Burden Class II.
There are smart ways of simply not acquiring some sequences of the usual clinical protocol, named “Abbreviated” MRI\textsuperscript{16} that led to reduced time of interpretation and scan time by acquiring only a pre-contrast and single post contrast T1-weighted sequence, using the maximum intensity projections (MIP) to obtain just one single high-contrast image.

**Figure 5.** Screening mammography shows a developing focal asymmetry with associated distortion. (A) shows the left craniocaudal view and (B) shows the left mediolateral oblique view mammography. Digital breast tomosynthesis slices (not shown here) demonstrated persistent findings and a diagnostic focused sonography (C) of the left breast did not show presence of a true mass lesion associated to a focal region of decreased echogenicity correlation. Figure D is the 3D-MIP images of the 2nd minute. The diagnostic problem-solving breast MRI does not show evidence of recurrent cancer, showing scar tissues without evidence of suspicious post gadolinium enhancement.
Does Breast MRI take less time to be reported or to be performed? In the last few years different names for breast DCE-MRI started popping up in the media for layperson and the scientific literature: abbreviated MRI also called “fast MRI” or AB-MR, abridged MRI, Ultrafast MRI, etc. They are not synonyms and do not have the same technique or carry the same MRI protocol, however all have the aim to decrease time and consequently the expectations of reducing costs associated with the standard-of-care breast DCE-MRI.

The term “Ultrafast MRI” has been used in Abdominal, Cardio and Neuro Imaging since the early 90’s 87-89 to describe process of decreasing sequence’s time and increasing from a fraction of a second90 to a fraction of a millisecond temporal resolution.91,92 The “Ultrafast” breast DCE-MRI93-95 sequences currently take over 5 seconds and are time-resolved magnetic resonance angiography (MRA) sequences with under sampling of the k-space periphery and using view-sharing that allows rapid acquisition of multiple images during the passage of the contrast bolus.

The concept is simple as a wave is characterized by its wavelength (λ), the distance between 2 corresponding points or successive peaks. The wavenumber (k) is simply the number of waves or cycles per unit distance. A typical time resolved MRA study might contain more than 20 images obtained at rates as rapid as 1-2 frames per second. Inevitably there is an inherent trade-off between spatial and temporal resolution for...
those techniques. The center of k-space has information about basic image contrast, while the details and edges are encoded in the peripheral k-space. The temporal resolution is highly impacted if sampling more points are required. For this reason, those time-resolved MRA techniques balance these competing resolution requirements using what is called view-sharing that is a process that start with a pre-contrast, full-resolution image of the area of interest followed by changes in the sampling of the k-space, e.g. during the passing of the contrast bolus, the center of k-space is sampled much more frequently than the periphery. The data from those different k-space sampling is then combined in order to create a series of time-resolved images with satisfactory spatial-resolution and pre-contrast full resolution image can be used as a mask for subtraction improving vascular conspicuity.

The time-resolved MRA techniques currently used in Breast MR imaging acquire 3D k-space typically using radial sampling schemes in round or oval “cylinders” and they are vendor based. For example, in our institution we have Siemens’ scanners, and it is named as TWIST (“Time-resolved angiography With Stochastic Trajectories”)96; Phillips uses the name of 4D-TRAK (“4D Time-Resolved Angiography using Keyhole”)97; General Electric (GE) calls theirs as TRICKS (“Time-Resolved Imaging of Contrast Kinetics”)98; Toshiba named Freeze Frame29 and Hitachi named TRAQ (“Time-Resolved AcQuisition”).100

All time-resolved MRA techniques carry a 3D-spoiled gradient echo sequences with thin slices, very short TRs and TEs, low flip angles and parallel imaging acquisition, similar to the DCE-MRI sequences used in the breast. Specific k-space parameters must be selected, the size of the central k-space region, its refresh rate (in frames per second) and the total number of frames to be acquired. This process is all not currently standardized for breast MRI use and those specifications vary by vendor. The GE’s MRI sequence name DISCO (Differential Subsampling with Cartesian Ordering) shares similar features with the Siemens’ TWIST and their own sequence TRICKS which is used for dynamic perfusion imaging instead of for MRA. DISCO uses a dual-echo 3D SPGR sequence with pseudo-random variable density k-space segmentation and a view-sharing reconstruction to achieve high spatio-temporal resolution. The dual, i.e. in-phase and out-of-phase echoes allows separation of fat and water signals and this sequence can also achieve a strong fat suppression using a 2-point Dixon fat-water reconstruction algorithm. DISCO is used for breast DCE-MRI and subdivides k-space into several annular elliptical regions that are incompletely sampled and randomly together with a central k-space region that is consistently sampled.101

The first published study of the “Ultrafast Breast MRI” in 2014 using a time-resolved technique applied in breast imaging (TWIST) showed high sensitivity (90%) with very low specificity (67%).102 Other studies followed showing lower specificity of the fast protocols or the abbreviated ones compared to the full protocol. The differences however were not significant between the traditional full diagnostic protocol and the abbreviated ones.103,104 A recent systematic review and metaanalysis103 of available studies (2,763 women with 3,251 screening rounds) comparing the standard (full) protocols with the short (abbreviated) DCE-MRI protocols shows very low level of evidence to suggest that the abridged protocols could be accurate for breast cancer screening. Systematic reviews and metaanalysis focusing exclusively on what is called “Ultrafast Breast MRI” are not yet available.

**Essential Breast MRI Should be Reproducible**

To date there is no standardization for the DCE-MRI protocols105-111 either for traditional ones with averaged time of 3 min to 7 min post-GBCA or the abbreviated ones where a single point post contrast is obtained with the expectation that no enhancement at all is detected. There is even less standardization for the “ultrafast breast MRI.”80,88 Indeed, there isn’t full agreement about what exactly is meant by “Ultrafast” for other subspecialties.112,113 On the other hand, the International Breast Diffusion-Weighted Imaging Working group have established basic requirements about DWI-MRI protocols used in association to DCE-MRI in the Multiparametric Breast MRI112 in order to have the diffusion breast MRI incorporated to the BIRADS in the near future.

**One Step Forward and Two Steps Fast Forward**

Current clinical practice shows that adding Diffusion-MRI (either DWI-MRI or DTI-MRI) is helpful to increase specificity4,95 of DCE-MRI (Multiparametric Breast MRI). The T2-weighted imaging can be interchangeable with the b0 images (b value = 0 s/mm2) from the Diffusion-MRI decreasing time. In order to achieve this interchangeable status, the amount of noise must be minimal, and the fat suppression should be optimized which is a limitation if scanners are not optimized and calibrated for diffusion sequences.25,55,84

The Multiparametric Breast MRI (Table 2) is appropriate to be used in Diagnostic Breast MRI and the patient’s time in the scanner would range 4-8 min for the diffusion sequences and 4-7 min for the DCE-MRI (T1-weighted fat suppressed 3D gradient echo (GE) pulse sequence obtained before contrast injection and then repeated as rapidly as possible during 4-5 min after GBCA injection, with slice thickness of 3 mm or less and in-plane resolution of 1 mm or less). If GBCA-free T1-weighted images for the higher axillary regions or GBCA-free T2-weighted images without or with fat suppression (Dixon with both water and fat suppression is considered) are required because of poor quality b0 images additional time may range up to 4-12 min for both sequences. This full protocol has a total duration of 8 to 27 minutes scanning plus patient’s time in and out scanner. To overcome those long scan times in toto that may limit the widespread use of breast MRI for all patients, protocols that shorten the image acquisition are appealing and called as abbreviated shortened.
**Table 2. Comparison Among the Different Breast MRI Clinical Protocols.**

| Multiparametric breast MRI | Abbreviated screening breast MRI | Ultrafast breast MRI 3 T GE scanner | Ultrafast breast MRI 3 T Siemens scanner |
|---------------------------|----------------------------------|------------------------------------|----------------------------------------|
| DI (DWI or DTI) in lieu of T2-W FS (STIR) or DIXON FS WS | T2-W FS (STIR) or DIXON FS WS (optional if optimal DI done) | T2-W FS (STIR) or DIXON FS WS (optional if optimal DI done) | |
| T1-W without FS | T1-W without FS (not for screening) | T1-W without FS (not for screening) | T1-W 3D FS TWIST pre Gd |
| T1-W 3D GE FS pre Gd | T1-W 3D GE FS DISCO pre Gd | T1-W 3D FS DISCO 3.5 sec post Gd | T1-W 3D FS TWIST 20.5 sec post Gd |
| T1-W 3D GE FS 1 min post Gd | T1-W 3D GE FS 1 min post Gd | T1-W 3D FS DISCO 7 sec post Gd | T1-W 3D FS TWIST 25.1 sec post Gd |
| T1-W 3D GE FS 2 min post Gd | T1-W 3D GE FS DISCO 3.5 sec post Gd | T1-W 3D FS DISCO 7 sec post Gd | T1-W 3D FS TWIST 29.6 sec post Gd |
| T1-W 3D GE FS 3 min post Gd | T1-W 3D GE FS DISCO 10.5 sec post Gd | T1-W 3D FS DISCO 13.5 sec post Gd | T1-W 3D FS TWIST 32.6 sec post Gd |
| T1-W 3D GE FS 5 min post Gd (delayed) | T1-W 3D FS DISCO 14 sec post Gd | T1-W 3D FS TWIST 34.1 sec post Gd | T1-W 3D FS TWIST 34.1 sec post Gd |
| T1-W 3D FS DISCO 17.5 sec post Gd | T1-W 3D FS TWIST 38.6 sec post Gd | T1-W 3D FS TWIST 38.6 sec post Gd | T1-W 3D FS TWIST 38.6 sec post Gd |
| T1-W 3D FS DISCO 21 sec post Gd | T1-W 3D FS TWIST 43.1 sec post Gd | T1-W 3D FS TWIST 43.1 sec post Gd | T1-W 3D FS TWIST 43.1 sec post Gd |
| T1-W 3D FS DISCO 24.5 sec post Gd | T1-W 3D FS TWIST 47.7 sec post Gd | T1-W 3D FS TWIST 47.7 sec post Gd | T1-W 3D FS TWIST 47.7 sec post Gd |
| T1-W 3D FS DISCO 29 sec post Gd | T1-W 3D FS TWIST 52.2 sec post Gd | T1-W 3D FS TWIST 52.2 sec post Gd | T1-W 3D FS TWIST 52.2 sec post Gd |
| T1-W 3D FS DISCO 31.5 sec post Gd | T1-W 3D FS TWIST 56.7 sec post Gd | T1-W 3D FS TWIST 56.7 sec post Gd | T1-W 3D FS TWIST 56.7 sec post Gd |
| T1-W 3D FS DISCO 35 sec post Gd | T1-W 3D FS TWIST 61.2 sec post Gd | T1-W 3D FS TWIST 61.2 sec post Gd | T1-W 3D FS TWIST 61.2 sec post Gd |
| T1-W 3D FS DISCO 38.5 sec post Gd | T1-W 3D FS TWIST 65.8 sec post Gd | T1-W 3D FS TWIST 65.8 sec post Gd | T1-W 3D FS TWIST 65.8 sec post Gd |
| T1-W 3D FS DISCO 42 sec post Gd | T1-W 3D FS TWIST 70.3 sec post Gd | T1-W 3D FS TWIST 70.3 sec post Gd | T1-W 3D FS TWIST 70.3 sec post Gd |
| T1-W 3D FS DISCO 45.5 sec post Gd | T1-W 3D FS TWIST 74.8 sec post Gd | T1-W 3D FS TWIST 74.8 sec post Gd | T1-W 3D FS TWIST 74.8 sec post Gd |
| T1-W 3D FS DISCO 49 sec post Gd | T1-W 3D FS TWIST 79.3 sec post Gd | T1-W 3D FS TWIST 79.3 sec post Gd | T1-W 3D FS TWIST 79.3 sec post Gd |
| T1-W 3D FS DISCO 52.5 sec post Gd | T1-W 3D FS TWIST 83.8 sec post Gd | T1-W 3D FS TWIST 83.8 sec post Gd | T1-W 3D FS TWIST 83.8 sec post Gd |
| T1-W 3D FS DISCO 56 sec post Gd | T1-W 3D FS TWIST 88.3 sec post Gd | T1-W 3D FS TWIST 88.3 sec post Gd | T1-W 3D FS TWIST 88.3 sec post Gd |
| T1-W 3D FS DISCO 59.5 sec post Gd | T1-W 3D FS TWIST 92.8 sec post Gd | T1-W 3D FS TWIST 92.8 sec post Gd | T1-W 3D FS TWIST 92.8 sec post Gd |
| T1-W 3D GE FS DISCO 63 sec post Gd | T1-W 3D GE FS DISCO 92 sec post Gd | T1-W 3D GE FS DISCO 92 sec post Gd | T1-W 3D GE FS DISCO 100 sec post Gd |
| T1-W 3D GE FS 2 min post Gd | T1-W 3D GE FS 2 min post Gd | T1-W 3D GE FS 2 min post Gd | T1-W 3D GE FS 2 min post Gd (delayed) |
| T1-W 3D GE FS 3 min post Gd | T1-W 3D GE FS 3 min post Gd | T1-W 3D GE FS 3 min post Gd | T1-W 3D GE FS 5 min post Gd (delayed) |
| T1-W 3D GE FS 5 min post Gd (delayed) | T1-W 3D GE FS 5 min post Gd (delayed) | T1-W 3D GE FS 5 min post Gd (delayed) | T1-W 3D GE FS 5 min post Gd (delayed) |

*Ultrafast breast MRI is exemplified using the sequences DISCO (Differential Subsampling with Cartesian Ordering) and TWIST (Time-resolved angiography With Stochastic Trajectories) that are vendor based. The boldface values in the table shows the center of the k-space.*
The abbreviated breast MRI (Table 2) was adapted in the ECOG/ACRIN trial (EA1141) and is defined as having a total scan time of less than 10 min (including localizer) and including a T2 weighted sequence. The advantage of the abbreviated standard DCE-MRI techniques with or without adding the T2-weighted images components is to decrease the patient’s time in the scanner as well to improve the radiologist reading time with the goal of having an output of a simple binary answer to screening, yes or no presence of a potential actionable region of enhancement. Assuming absent enhancement equals negative screening, and a known high NPV with breast MRI data, a negative MIP image may lead to an interpreting time of less than 3 seconds, but caution is advised as some tumors may only be seen on the source images.

The “Ultrafast breast MRI” is composed of sequences that will shorten only the initial phase of the current DCE-MRI as the delayed phase is not usually done using this sequence (Table 2). It can be used with either diagnostic or screening Breast MRI, replacing the initial 0-60 seconds of the current DCE-MRI T1-weighted fat suppressed GE sequence that has one scan before contrast and 1 to 5 scans post contrast. The Ultrafast breast MRI generates consecutive images scanning using a fast temporal resolution after i.v contrast. There is no current determined optimal cut off value to the initial scanning and can be initiated at 3.5 seconds for 3 T magnets and 7 seconds for 1.5 T magnets keeping the slice thickness of 3 mm or less and the in-plane resolution of 1 mm or less.

Independent of using ultrafast temporal scanning, the classic Abbreviated MRI protocols, or the traditional protocols without fast temporal resolution breast DCE-MRI, it is recommended that post contrast image of maximum enhancement should have the center of the k-space (Figure 7) of ∼120 seconds post contrast administration. A dynamic sequence demands at least 3 time points to be measured: (1) one before the administration of GBCA, (2) one approximately 90 to 120 seconds later to capture the peak and (3) one in the late phase 5-7 min post contrast to evaluate whether a lesion continues to enhance, will show a plateau or will show early washout of the contrast agent (decrease of signal intensity). One study of Rapid Abridged Multiphase Protocol (RAMP) shortened breast MRI protocol found that kinetic analysis was reliable if the late phase obtained at 3-4 min. Some of the abbreviated MRI protocols that are solely based on MIP and one point after contrast do not allow determination of the enhancement curves. They are highly sensitive, but the specificity may decrease. In addition, generating MIP images leads to very fast lesion detection to the radiologist’s visual assessment, however chemical shift artifacts, suboptimal fat suppression and patient’s motion artifacts may cause poor MIP quality and obscure small lesions. For this reason, it makes sense to have an ideal breast MRI protocol that could

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**Figure 7.** The acquisition breast MRI protocols with their sequences are compared based on the timeline. (1) Patient’s registration time. (2) MRI preparation 1: safety screening. (3) MRI preparation 2: venepuncture first, and then positioning on the table. (4) Scout. (5) T1-weighted without fat suppression (covering axillary regions). (6) T2-weighted with fat suppression (e.g. STIR, “FAT-SAT,” SSFP). (7) DWI or DTI. (8) Ultrafast. (9) DCE. (10) Fat suppressed and water suppressed sequences (e.g. Dixon). The red arrows represent the moment when the GBCA intravascular injection occurred. The letter K with circle in blue present in all DCE sequences (9) indicates the center of k-space.
contemplate both screening and diagnostic indications having the shortest occupation of the scanner by the patient without compromising the tests results. One group investigated the use of diffusion techniques as a substitute of the DCE-MRI delayed phase in a diagnostic study of patients with equivocal or suspicious US and/or mammography.\textsuperscript{112} It was found that the initial enhancement rate (1 min post contrast) and ADC determined from DWI yield a higher AUC than a dynamic analysis with the late phase enhancement. Similar results were reported for a retrospective diagnostic study.\textsuperscript{95} This approach could be explored more broadly and systematically in prospective studies although the shortening of DCE scan still requires patient time and facilities for the injection procedure.

Whether combining what is suggested as a feasible state of the art “shortened” breast MRI protocol would be a simple equation: “Ultrafast” + Diffusion is an open question. All MRI techniques continue to evolve, Ultrafast Breast MRI is meant to replace the initial phase DCE-MRI; Diffusion should be done instead of T2-weighted images and possibly the delayed phase of DCE-MRI. Images to be reported available as postprocessed subtracted and non-subtracted images with MIP reconstruction, DWI and ADC maps or DTI color coded maps (\(\lambda-1, \lambda-2, \lambda-3,\) MA, FA, MD) and DTI-MIP. Further research is required to determine the effects of this shortened protocol on clinical outcomes.

**What Is Coming Up in Breast MRI**

To conclude this review, I would like to point out that other areas that are not MRI exclusive are the fields of artificial intelligence, machine learning tools and radiomics that will almost certainly facilitate the rapid improvement of clinical practice and consequently better patient care.\textsuperscript{116-119} Breast radiologists shall expect that the use of DeepContrast AI algorithms in gadolinium-free breast MR images may be a reliable tool to predict the contrast-enhancement completing the breast MRI history circle-of-life when i.v. contrast was not used.

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**References**

1. Kaiser WA. MR-Mammographie [in German]. Radiologe. 1993; 33(5):292-299.
2. Vaughan JT, Adriany G, Snyder CJ, et al. Efficient high-frequency body coil for high-field MRI. Magn Reson Med. 2004;52(4):851-859.
3. Hendrick RE. High-quality breast MRI. Radiol Clin North Am. 2014;52(3):547-562.
4. Zhang M, Horvat JV, Bernard-Davila B, et al. Multiparametric MRI model with dynamic contrast-enhanced and diffusion-weighted imaging enables breast cancer diagnosis with high accuracy. J Magn Reson Imaging. 2019;49(3):864-874.
5. Kuhl C. The current status of breast MR imaging. Part I. Choice of technique, image interpretation, diagnostic accuracy, and transfer to clinical practice. Radiology. 2007;244(2):356-378.
6. Heywang-Köbrunner SH, Wolf HD, Deimling M, Köbling S, Höfer H, Spielmann RP. Misleading changes of the signal intensity on opposed-phase MRI after injection of contrast medium. J Comput Assist Tomogr. 1996;20(2):173-178.
7. Veronesi U, Boyle P, Goldhirsch A, Orecchia R, Viale G. Breast cancer. Lancet. 2005;365(9472):1727-1741.
8. Buadu LD, Murakami J, Murayama S, et al. Patterns of peripheral enhancement in breast masses: correlation of findings on contrast medium enhanced MRI with histologic features and tumor angiogenesis. J Comput Assist Tomogr. 1997;21(3):421-430.
9. Costa AF, van der Pol CB, Maralani PJ, et al. Gadolinium deposition in the brain: a systematic review of existing guidelines and policy statement issued by the Canadian Association of Radiologists. Can Assoc Radiol J. 2018;69(4):373-382.
10. Murata N, Murata K, Gonzalez-Cuyar LF, Maravilla KR. Gadolinium tissue deposition in brain and bone. Magn Reson Imaging. 2016;34(10):1359-1365.
11. Ramalho J, Semelka RC, Ramalho M, Nunes RH, AIObaíd M, Castillo M. Gadolinium-based contrast agent accumulation and toxicity: an update. AJNR Am J Neuroradiol. 2016;37(7):1192-1198.
12. Stojanov D, Aracki-Trenkic A, Benedeto-Stojanov D. Gadolinium deposition within the dentate nucleus and globus pallidus after repeated administrations of gadolinium-based contrast agents-current status. Neuroradiology. 2016;58(5):433-441.
13. Kanda T, Ishii K, Kawaguchi H, Kitajima K, Takekna D. High signal intensity in the dentate nucleus and globus pallidus on unenhanced T1-weighted MR images: relationship with increasing cumulative dose of a gadolinium-based contrast material. Radiology. 2014;270(3):834-841.

14. Lancelot E, Desché P. Gadolinium retention as a safety signal: experience of a manufacturer. Invest Radiol. 2020;55(1):20-24.

15. Layne KA, Dargan PI, Archer JRH, Wood DM. Gadolinium deposition and the potential for toxicological sequelae—a literature review of issues surrounding gadolinium-based contrast agents. Br J Clin Pharmacol. 2018;84(11):2522-2534. doi:10.1111/bcp.13718

16. US Food & Drug Administration: FDA Drug Safety Communication. FDA warns that gadolinium-based contrast agents (GBCAs) are retained in the body; requires new class warnings. US Food & Drug Administration; Published 2018. Updated May 16, 2018. Accessed May 02, 2021. https://www.fda.gov/drugs/drugsafety-and-availability/fda-drug-safety-communication-fda-warns-gadolinium-based-contrast-agents-gbcas-are-retained-body

17. Nissan N, Furman-Haran E, Allweiss T, et al. Noncontrast breast MRI during pregnancy using diffusion tensor imaging: a feasibility study. J Magn Reson Imaging. 2019;49(2):508-517.

18. Nissan N, Anaby D, Sklair-Levy M. Breast MRI without contrast is feasible and appropriate during pregnancy. J Am Coll Radiol. 2019;16(4 Pt A):408-409.

19. Nissan N, Allweiss T, Menes T, et al. Breast MRI during lactation: effects on tumor conspicuity using dynamic contrast-enhanced (DCE) in comparison with diffusion tensor imaging (DTI) parametric maps. Eur Radiol. 2020;30(2):767-777.

20. Andreassen MMS, Rodriguez-Soto AE, Conlin CC, et al. Discrimination of breast cancer from healthy breast tissue using a three-component diffusion-weighted MRI model. Clin Cancer Res. 2021;27(4):1094-1104.

21. Clauser P, Krug B, Bickel H, et al. Diffusion-weighted imaging allows for downgrading MR BI-RADS 4 lesions in contrast-enhanced MRI of the breast to avoid unnecessary biopsy. Clin Cancer Res. 2021;27(7):1941-1948. doi:10.1158/1078-0432.CCR-20-1043. CCR-20-1043

22. Baltzer P, Mann RM, Ilma M, et al; EUSOBI International Breast Diffusion-Weighted Imaging working group. Diffusion-weighted imaging of the breast—a consensus and mission statement from the EUSOBI International Breast Diffusion-Weighted Imaging working group. Eur Radiol. 2020;30(3):1436-1450.

23. Baxter GC, Graves MJ, Gilbert FJ, Patterson AJ. A meta-analysis of the diagnostic performance of diffusion MRI for breast lesion characterization. Radiol. 2019;291(3):632-641.

24. Wang K, Li Z, Wu Z, et al. Diagnostic performance of diffusion tensor imaging for characterizing breast tumors: a comprehensive meta-analysis. Front Oncol. 2019;9:1229.

25. Furman-Haran E, Eyal E, Shapiro-Feinberg M, et al. Advantages and drawbacks of breast DTI. Eur J Radiol. 2012;81(suppl 1):S45-S47.

26. Scaranelo AM, Degani H, Grobgeld D, Talbot N, Bodolai K, Furman-Haran E. Effect of IV administration of a gadolinium-based contrast agent on breast diffusion-tensor imaging. AJR Am J Roentgenol. 2020;215(4):1030-1036.

27. Spick C, Szolar DHM, Preidler KW, et al. 3 Tesla breast MR imaging as a problem-solving tool: diagnostic performance and incidental lesions. PLoS One. 2018;13(1):e0190287.

28. Dorrius MD, Pijnappel RM, van der Weide MCI, Oudkerk M. Breast magnetic resonance imaging as a problem-solving modality in mammographic BI-RADS 3 lesions. Cancer Imaging. 2010;10 Spec no A(1A):S54-S58.

29. Pinker K, Møy L, Sutton EJ, et al. Diffusion-weighted imaging with apparent diffusion coefficient mapping for breast cancer detection as a stand-alone parameter: comparison with dynamic contrast-enhanced and multiparametric magnetic resonance imaging. Invest Radiol. 2018;53(10):587-595.

30. Baltzer PAT, Kapetas P, Sodaño C, et al. Kontrastmittel-unzulässig: MRT: vorteile und potenzielle nachteile [in German]. [Contrast agent-free breast MRI: advantages and potential disadvantages]. Radiol. 2019;59(6):510-516.

31. Goldammer F, Pinsolle V, Dissa C, Péliassier P. Accuracy of mammography, sonography and magnetic resonance imaging for detecting silicone breast implant ruptures: a retrospective observational study of 367 cases. Ann Chir Plast Esthet. 2021;66(1):25-41.

32. Scaranelo AM, Marques AF, Smialowski EB, Lederman HM. Evaluation of the rupture of silicone breast implants by mammography, ultrasonography and magnetic resonance imaging in asymptomatic patients: correlation with surgical findings. Sao Paulo Med J. 2004;122(2):41-47.

33. Goodman CM, Cohen V, Thony J, Netscher D. The life span of silicone gel breast implants and a comparison of mammography, ultrasonography, and magnetic resonance imaging in detecting implant rupture: a meta-analysis. Ann Plast Surg. 1998;41(6):577-585; discussion 585-586.

34. Gorczyca DP, Gorczyca SM, Gorczyca KL. The diagnosis of silicone breast implant rupture. Plast Reconstr Surg. 2007;120(7 suppl 1):498S-61S. doi:10.1097/01. PRS.0000300587.00000010.

35. Sharma B, Jurgensen-Rauch A, Pace E, et al. Breast implant-associated anaplastic large cell lymphoma: review and multiparametric imaging paradigms. Radiographics. 2020;40(3):609-628.

36. Clemens MW, Jacobsen ED, Horwitz SM. 2019 NCCN consensus guidelines on the diagnosis and treatment of breast implant-associated anaplastic large cell lymphoma (BIA-ALCL). Aesthet Surg J. 2019;39(suppl 1):S3-S13.

37. Society’s Research Committee. Consensus Guideline on Diagnostic and Screening Magnetic Resonance Imaging of the Breast Cancer. The American Society of Breast Surgeons; Published 2017. Updated June 27, 2017. Accessed March 27, 2021. https://www.breastsurgeons.org/docs/statements/Consensus-Guideline-on-Diagnostic-and-Screening-Magnetic-Resonance-Imaging-of-the-Breast.pdf

38. Morris EA, Schwartz LH, Dershaw DD, van Zee KJ, Abramson AF, Liberman L. MR imaging of the breast in patients with occult primary breast carcinoma. Radiology. 1997;205(2):437-440.

39. Lee CH, Dershaw DD, Kopans D, et al. Breast cancer screening with imaging: recommendations from the Society of Breast Imaging and the ACR on the use of mammography, breast MRI, breast...
ultrasound, and other technologies for the detection of clinically occult breast cancer. *J Am Coll Radiol.* 2010;7(1):18-27.

40. Kim H, Park W, Kim SS, et al. Outcome of breast-conserving treatment for axillary lymph node metastasis from occult breast cancer with negative breast MRI. *Breast.* 2020;49:63-69.

41. Harms SE, Flamig DP, Hesley KL, et al. MR imaging of the breast with rotating delivery of excitation off resonance: clinical experience with pathologic correlation. *Radiology.* 1993;187(2):493-501.

42. Orel SG, Schnall MD, Powell CM, et al. Staging of suspected breast cancer: effect of MR imaging and MR-guided biopsy. *Radiology.* 1995;196(1):115-122.

43. Fischer U, Kopka L, Grabbe E. Breast carcinoma: effect of preoperative contrast-enhanced MR imaging on the therapeutic approach. *Radiology.* 1999;213(3):881-888.

44. Houssami N, Turner R, Morrow M. Preoperative magnetic resonance imaging in breast cancer: meta-analysis of surgical outcomes. *Ann Surg.* 2013;257(2):249-255.

45. Gonzalez V, Sandelin K, Karlsson A, et al. Preoperative MRI of the breast (POMB) influences primary treatment in breast cancer: a prospective, randomized, multicenter study. *World J Surg.* 2014;38(7):1685-1693.

46. Arnaout A, Catley C, Booth CM, et al. Use of preoperative magnetic resonance imaging for breast cancer: a Canadian population-based study. *JAMA Oncol.* 2015;1(9):1238-1250.

47. Houssami N, Turner RM, Morrow M. Meta-analysis of preoperative magnetic resonance imaging (MRI) and surgical treatment for breast cancer. *Breast Cancer Res Treat.* 2017;165(2):273-283.

48. Dent BL, Miller JA, Eden DJ, Swistel A, Talmor M. Tumor-to- nipple distance as a predictor of nipple involvement: expanding the inclusion criteria for nipple-sparing mastectomy. *Plast Reconstr Surg.* 2017;140(1):1e-8e.

49. Thompson JL, Wright GP. The role of breast MRI in newly diagnosed breast cancer: an evidence-based review. *Am J Surg.* 2021;221(3):525-528.

50. Kuhl C, Kuhn W, Braun M, Schild H. Pre-operative staging of breast cancer with breast MRI: one step forward, two steps back? *Breast.* 2007;16(suppl 2):S34-S44.

51. Simmons CE, Hogeveen S, Leonard R, et al. A Canadian national expert consensus on neoadjuvant therapy for breast cancer: linking practice to evidence and beyond. *Curr Oncol.* 2015;22(suppl 1):S43-S53.

52. Expert Panel on Breast Imaging; Slanetz PJ, Moy L, et al. ACR appropriateness criteria® monitoring response to neoadjuvant systemic therapy for breast cancer. *J Am Coll Radiol.* 2017;14(11 suppl):S462-S475.

53. Partridge SC, Gibbs JE, Lu Y, Esserman LJ, Sudilovsky D, Hylton NM. Accuracy of MR imaging for revealing residual breast cancer in patients who have undergone neoadjuvant chemotherapy. *AJR Am J Roentgenol.* 2002;179(5):1193-1199.

54. Wu LM, Hu JN, Gu HY, Hua J, Chen J, Xu JR. Can diffusion-weighted MR imaging and contrast-enhanced MR imaging precisely evaluate and predict pathological response to neoadjuvant chemotherapy in patients with breast cancer? *Breast Cancer Res Treat.* 2012;135(1):17-28.

55. Furman-Haran E, Nissan N, Ricart-Selva V, Martinez-Rubio C, Degani H, Camps-Herrero J. Quantitative evaluation of breast cancer response to neoadjuvant chemotherapy by diffusion tensor imaging: initial results. *J Magn Reson Imaging.* 2018;47(4):1080-1090.

56. Marinovich ML, Sardanelli F, Ciatto S, et al. Early prediction of pathologic response to neoadjuvant therapy in breast cancer: systematic review of the accuracy of MRI. *Breast.* 2012;21(5):669-677.

57. Santamaría G, Bargalló X, Fernández PL, Farrús B, Caparrós X, Velasco M. Neoadjuvant systemic therapy in breast cancer: association of contrast-enhanced MR imaging findings, diffusion-weighted imaging findings, and tumor subtype with tumor response. *Radiology.* 2017;283(3):663-672.

58. Lee JM, Orel SG, Czernecki BJ, Solin LJ, Schnall MD. MRI before reexcision surgery in patients with breast cancer. *AJR Am J Roentgenol.* 2004;182(2):473-480.

59. Frei KA, Kinkel B, Bonel HM, Lu Y, Esserman LJ, Hylton NM. MR imaging of the breast in patients with positive margins after lumpectomy: influence of the time interval between lumpectomy and MR imaging. *AJR Am J Roentgenol.* 2000;175(6):1577-1584.

60. Krammer J, Price ER, Joehlson MS, et al. Breast MR imaging for the assessment of residual disease following initial surgery for breast cancer with positive margins. *Eur Radiol.* 2017;27(11):4812-4818.

61. Lee CH, Smith RC, Levine JA, Trojan RN, Tocino I. Clinical usefulness of MR imaging of the breast in the evaluation of the problematic mammogram. *AJR Am J Roentgenol.* 1999;173(5):1323-1329.

62. Taşkın F, Polat Y, Erdoğan İH, Türköğlu FT, Öztürk VS, Özbah S. Problem-solving breast MRI: useful or a source of new problems? *Diagn Interv Radiol.* 2018;24(5):255-261.

63. Amitai Y, Scaranelo A, Menes TS, et al. Can breast MRI accurately exclude malignancy in mammographic architectural distortion? *Eur Radiol.* 2020;30(5):2751-2760.

64. Rotili A, Ferrari F, Nicosia L, et al. MRI features of breast implant-associated anaplastic large cell lymphoma. *Br J Radiol.* 2021;20210093. doi: 10.1259/bjr.20210093

65. Kuhl CK, Schmutzler RK, Leutner CC, et al. Breast MR imaging screening in 192 women proved or suspected to be carriers of a breast cancer susceptibility gene: preliminary results. *Radiology.* 2000;215(1):267-279.

66. Wang L, Strigel RM. Supplemental screening for patients at intermediate and high risk for breast cancer. *Radiol Clin North Am.* 2021;59(1):67-83.

67. Gao Y, Goldberg JE, Young TK, Babb JS, Moy L, Heller SL. Breast cancer screening in high-risk men: a 12-year longitudinal observational study of male breast imaging utilization and outcomes. *Radiology.* 2019;293(2):282-291.

68. Canadian Cancer Statistics Advisory Committee. *Canadian Cancer Statistics 2019.* Canadian Cancer Society; Published 2019. Updated September, 2019. Accessed March 27, 2021. https://cancer.ca/Canadian-Cancer-Statistics-2019-EN

69. Warner E, Messersmith H, Causer P, Eisen A, Shumak R, Plewe DS. Systematic review: using magnetic resonance imaging to screen women at high risk for breast cancer. *Ann Intern Med.* 2008;149(9):671-679.
70. Sardanelli F, Podo F, Santoro F, et al; High Breast Cancer Risk Italian 1 (HIBCRIT-1) Study. Multicenter surveillance of women at high genetic breast cancer risk using mammography, ultrasonography, and contrast-enhanced magnetic resonance imaging (the high breast cancer risk Italian 1 study): final results. Invest Radiol. 2011;46(2):94-105.

71. Lo G, Scaranello AM, Aboras H, et al. Evaluation of the utility of screening mammography for high-risk women undergoing screening breast MR imaging. Radiology. 2017;285(1):36-43.

72. Saadatmand S, Geuzinge HA, Rutgers EJT, et al; FaMRIsc Study Group. MRI versus mammography for breast cancer screening in women with familial risk (FaMRisc): a multicentre, randomised, controlled trial. Lancet Oncol. 2019;20(8):1136-1147.

73. Comstock CE, Gatsonis C, Newstead GM, et al. Comparison of abbreviated breast MRI vs digital breast tomosynthesis for breast cancer detection among women with dense breasts undergoing screening. JAMA. 2020;323(8):746-756.

74. D’Orsi CJ, Sickles EA, Mendelson EB, Morris EA. ACR BI-RADS® Atlas. Breast Imaging Reporting and Data System. American College of Radiology; 2013.

75. Brown J, Smith RC, Lee CH. Incidental enhancing lesions found on MR imaging of the breast. AJR Am J Roentgenol. 2001;176(5):1249-1254.

76. Bakker MF, de Lange SV, Pijnappel RM, et al; DENSE Trial Study Group. Supplemental MRI screening for women with extremely dense breast tissue. N Engl J Med. 2019;381(22):2091-2102.

77. Vreemann S, Gubern-Merida A, Lardenoije S, et al. The frequency of missed breast cancers in women participating in a high-risk MRI screening program. Breast Cancer Res Treat. 2018;169(2):323-331.

78. Lamb LR, Mohallem Fonseca M, Verma R, Seely JM. Missed breast cancer: effects of subconscious bias and lesion characteristics. Radiographics. 2020;40(4):941-960.

79. Stackner SA, Williams SP, Karnezis T, Shayan R, Fox SB, Achen MG. Lymphangiogenesis and lymphatic vessel remodelling in cancer. Nat Rev Cancer. 2014;14(3):159-172.

80. Tofts PS, Brix G, Buckley DL, et al. Estimating kinetic parameters from dynamic contrast-enhanced T(1)-weighted MRI of a diffusible tracer: standardized quantities and symbols. J Magn Reson Imaging. 1999;10(3):223-232.

81. Degani H, Guisis V, Weinstein D, Fields S, Strano S. Mapping pathophysiologic features of breast tumors by MRI at high spatial resolution. Nat Med. 1997;3(7):780-782.

82. Weinstein D, Strano S, Cohen P, Fields S, Gomori JM, Degani H. Breast fibroadenoma: mapping of pathophysiologic features with three-time-point, contrast-enhanced MR imaging—pilot study. Radiology. 1999;210(1):233-240.

83. Furman-Haran E, Degani H. Parametric analysis of breast MRI. J Comput Assist Tomogr. 2002;26(3):376-386.

84. Eyal E, Shapiro-Feinberg M, Furman-Haran E, et al. Parametric diffusion tensor imaging of the breast. Invest Radiol. 2012;47(5):284-291.

85. Boetes C, Barentsz JO, Mus RD. MR characterization of suspicious breast lesions with a gadolinium-enhanced TurboFLASH subtraction technique. Radiology. 1994;193(3):777-781.

86. Kuhl CK, Schrading S, Strobel K, Schild HH, Hilgers RD, Bieling HB. Abbreviated breast magnetic resonance imaging (MRI): first postcontrast subtracted images and maximum-intensity projection—a novel approach to breast cancer screening with MRI. J Clin Oncol. 2014;32(22):2304-2310.

87. Stehling MK, Charnley RM, Blamire AM, et al. Ultrafast magnetic resonance scanning of the liver with echo-planar imaging. Br J Radiol. 1990;63(750):430-437.

88. Cohen MS, Weisskoff RM. Ultra-fast imaging. Magn Reson Imaging. 1991;9(1):1-37.

89. van Ruy GC, van der Wall EE, van Dijkman PR, Louwerenburg HW, de Roos A, Bruschke AV. Usefulness of ultrafast magnetic resonance imaging in healed myocardial infarction. Am J Cardiol. 1992;70(15):1233-1237.

90. Aronen HJ, Cohen MS, Belliveau JW, Fordham JA, Rosen BR. Ultrafast imaging of brain tumors. Top Magn Reson Imaging. 1993;5(1):14-24.

91. Zhong Z, Sun K, Karaman MM, Zhou XJ. Magnetic resonance imaging with submillisecond temporal resolution. Magn Reson Med. 2021;85(5):2434-2444.

92. Gao Y, Heller SL. Abbreviated and ultrafast breast MRI in clinical practice. Radiographics. 2020;40(6):1507-1527.

93. Vreemann S, Rodriguez-Ruiz A, Nickel D, et al. Compressed sensing for breast MRI: resolving the trade-off between spatial and temporal resolution. Invest Radiol. 2017;52(10):574-582.

94. Peter SC, Wenkel E, Weiland E, et al. Combination of an ultrafast TWIST-VIBE dixon sequence protocol and diffusion-weighted imaging into an accurate easily applicable classification tool for masses in breast MRI. Eur Radiol. 2020;30(5):2761-2772.

95. Ohashi A, Kataoka M, Iima M, et al. A multiparametric approach to diagnosing breast lesions using diffusion-weighted imaging and ultrafast dynamic contrast-enhanced MRI. Magn Reson Imaging. 2020;71:154-160.

96. Hennig J, Scheffler K, Laubenberger J, Streecker R. Time-resolved projection angiography after bolus injection of contrast agent. Magn Reson Med. 1997;37(3):341-345.

97. Willinek WA, Hadizadeh DR, von Falkenhausen M, et al. 4D time-resolved MR angiography and ultrafast dynamic contrast-enhanced MRI. Magn Reson Med. 2008;60(6):1455-1460.

98. Korosec FR, Frayne R, Gris TM, Mistretta CA. Time-resolved contrast-enhanced 3D MR angiography. Magn Reson Med. 1996;36(3):345-351.

99. Toshiba Expands Capabilities of Non-contrast MR Angiography Technique. Canon Medical Systems USA. News Press Release; Published 2005. Updated June 24, 2005. Accessed March 26, 2021. https://us.medical.canon/news/press-releases/2005/06/24/61/.

100. Milon A, Wahab CA, Kermarrec E, Bekhouche A, Taourel P, Thomassin-Nagata I. Breast MRI: is faster better? AJR Am J Roentgenol. 2020;214(2):282-295.

101. Morrison CI, Henze Bancroft LC, DeMartini WB, et al. Novel high spatiotemporal resolution versus standard-of-care dynamic
contrast-enhanced breast MRI: comparison of image quality. *Invest Radiol.* 2017;52(4):198-205.

102. Mann RM, Mus RD, van Zelst J, Geppert C, Karssemeijer N, Platel B. A novel approach to contrast-enhanced breast magnetic resonance imaging for screening: high-resolution ultrafast dynamic imaging. *Invest Radiol.* 2014;49(9):579-585.

103. Geach R, Jones LI, Harding SA, et al; FAST MRI Study Group. The potential utility of abbreviated breast MRI (FAST MRI) as a tool for breast cancer screening: a systematic review and meta-analysis. *Clin Radiol.* 2021;76(2):e11-e154.e22.

104. Baxter GC, Selamoglu A, Mackay JW, Bond S, Gray E, Gilbert FJ. A meta-analysis comparing the diagnostic performance of abbreviated MRI and a full diagnostic protocol in breast cancer. *Clin Radiol.* 2021;76(2):e23-e154.e32.

105. Clauser P, Mann R, Athanasiou A, et al. A survey by the European Society of Breast Imaging on the utilisation of breast MRI in clinical practice. *Eur Radiol.* 2018;28(5):1909-1918.

106. Canadian Association of Radiologists. *CAR Standard for Magnetic Resonance Imaging. H: Breast Imaging.* Canadian Association of Radiologists. Published 2011. Updated April 28, 2011. Accessed March 12, 2021. https://car.ca/wp-content/uploads/Magnetic-Resonance-Imaging-2011.pdf

107. Canadian Association of Radiologists. *CAR Practice Guidelines and Technical Standards for Breast Imaging and Intervention. 3: Breast MRI.* Canadian Association of Radiologists. Published 2016. Updated November 28, 2016. Accessed November 28, 2016. https://car.ca/wp-content/uploads/car_breastimagingguidelines_2016_en.pdf

108. British Society of Breast Radiology. *BSBR Guidelines.* Breast MRI: guidelines from the European Society of Breast Imaging. Published 2008. Updated April 4, 2008. Accessed July 12, 2012. https://breastradiology.org/guidelines/

109. The Royal Australian and the New Zealand College of Radiologists. *RANZCR Guidelines.* Diagnostic Imaging Clinical Committee—Breast Imaging. Updated October 26, 2018. Accessed July 12, 2021. https://www.ranzcr.com/whats-on/news-media/287-ranzcr-submission-to-the-report-from-the-diagnostic-imaging-clinical-committee-breast-imaging

110. American College of Radiology. ACR practice parameter for the performance of contrast-enhanced magnetic resonance imaging (MRI) of the breast. Published 2018. Accessed July 12, 2021. https://www.acr.org/-/media/ACR/Files/Practice-Parameters/MR-Contrast-Breast.pdf

111. NHS Cancer Screening Programmes. *Technical Guidelines for Magnetic Resonance Imaging (MRI) for the Surveillance or Women at Higher Risk of Developing Breast Cancer.* NHSBSP Publication. Published 2013. Updated December 06, 2012. Accessed July 12, 2021. https://www.gov.uk/government/publications/nhs-breast-screening-using-mri-with-higher-risk-women

112. Greve T, Sollmann N, Hock A, Zimmer C, Kirschke JS. Novel ultrafast spiral head MR angiography compared to standard MR and CT angiography. *J Neuroimag.* 2021;31(1):45-56.

113. Ha JY, Baek HJ, Ryu KH, et al. One-minute ultrafast brain MRI with full basic sequences: can it be a promising way forward for pediatric neuroimaging? *AJR Am J Roentgenol.* 2020;215(1):198-205.

114. Choudhery S, Chou SS, Chang K, Kalpathy-Cramer J, Lehman CD. Kinetic analysis of lesions identified on a rapid abridged multiphase (RAMP) breast MRI protocol. *Acad Radiol.* 2020;27(5):672-681. doi:10.1016/j.acra.2019.05.001

115. Dietzel M, Ellmann S, Schulz-Wendtland R, et al. Breast MRI in the era of diffusion weighted imaging: do we still need signal-intensity time curves? *Eur Radiol.* 2020;30(1):47-56.

116. Sheth D, Giger ML. Artificial intelligence in the interpretation of breast cancer on MRI. *J Magn Reson Imaging.* 2020;51(5):1310-1324.

117. Jiang Y, Edwards AV, Newstead GM. Artificial intelligence applied to breast MRI for improved diagnosis. *Radiology.* 2021;305(1):38-46.

118. Codari M, Schiaffino S, Sardanelli F, Trimboli RM. Artificial intelligence for breast MRI in 2008-2018: a systematic mapping review. *AJR Am J Roentgenol.* 2019;212(2):280-292.

119. Yu X, Kang C, Guttery DS, Kadry S, Chen Y, Zhang YD. ResNet-SCDA-50 for breast abnormality classification. *IEEE/ACM Trans Comput Biol Bioinform.* 2021;18(1):94-102.