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Role of Breast MRI in Patients with Newly Diagnosed Breast Cancer

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Abstract The role of breast MRI in patients with newly diagnosed breast cancer is controversial. Preoperative MRI is highly sensitive and accurate in assessing tumor size, extensive intraductal component (EIC), and in detection of additional sites of disease. It also has utility in assessing chest wall, nipple-areolar complex, and nodal involvement. Yet there are conflicting results in whether the use of preoperative MRI improves re-excision rate, local recurrence rate, and ultimately, survival. MRI has also been associated with overestimation of disease and increased mastectomy rates, and may contribute to treatment delay. Nevertheless, certain subgroups of patients may benefit more from preoperative MRI than others, including those with invasive lobular cancer (ILC), dense breasts, and those at elevated risk for breast cancer.

Keywords Breast MRI · Preoperative breast MRI · Preoperative breast imaging · Breast cancer · Disease extent · Multifocal · Multicentric · Re-excision · Recurrence · Mastectomy rate · Locoregional staging

Introduction

Magnetic resonance imaging (MRI) is highly sensitive and accurate for diagnosis of breast cancer. Although breast MRI has become widely utilized in locoregional staging of newly diagnosed breast cancer [1, 2], its clinical benefits are unclear. Despite superior diagnostic accuracy of breast MR over mammography and ultrasound in characterizing disease burden [3–21], there are conflicting results in whether the use of preoperative breast MR improves re-excision rate, local recurrence rate, and ultimately, survival. Concerns of overestimation of disease [3, 22–24] and increased mastectomy rate [22, 25, 26] have also been raised. This is reflected in the paucity of standardized recommendations regarding the use of preoperative breast MRI from diagnostic imaging and surgical societies [27–30]. In this article, we will review strengths of breast MR in locoregional staging, discuss controversies surrounding its use, and review relevant current literature. We will also highlight subgroups of patients who may benefit most from a preoperative breast MR and clinical scenarios where breast MR is the most helpful.

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Strengths of Breast MR in Locoregional Disease Staging

Size and Extent of Known Tumor

Index Tumor

When compared to the diagnostic performance of 2D mammography, digital breast tomosynthesis (DBT), and ultrasound, MRI has been shown to have improved sensitivity and superior accuracy in estimating tumor size [3–14, 31] (Fig. 1). In a study by Berg et al., MRI outperformed mammography in detecting all histologic tumor types and had higher sensitivity than ultrasound for the detection of ductal carcinoma in situ (DCIS) [3]. Though overestimation does occur, improved correlation of MRI with pathologic index lesion size has been consistently demonstrated in multiple

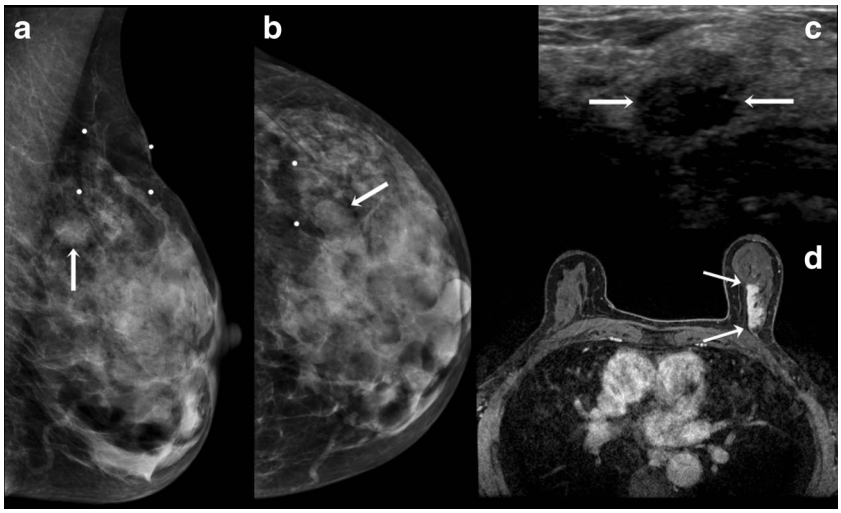

Fig. 1 Sixty-two-year old female presented with palpable abnormality in the upper outer quadrant of left breast, found to have a mass measuring approximately 1 cm on the mammogram in MLO (**a**) and CC (**b**) views (*arrows*), and on ultrasound (**c**) (*arrows*). Contrast-enhanced MRI (**d**) showed much more extensive disease measuring at least 3–4 cm in the largest dimension (*arrows*)

studies [4–7]. Even higher correlation with final pathology lesion size has been demonstrated with 3 T magnets over 1.5 T [32].

Extensive Intraductal Component

Accurate estimation of size and extent of disease depends on the ability to adequately assess the degree of surrounding extensive intraductal component (EIC) associated with the primary tumor [33]. The entire extent of disease including the index tumor and its surrounding EIC determines candidacy for breast conservation therapy (BCT) and defines the margins of excision. Improved accuracy of MRI over mammography in estimating the size of surrounding EIC has been consistently reported [3, 12–14]. The overall sensitivity of MRI for EIC varies between studies. A meta-analysis by Schouten van der Velden in 2009 found a wide range of sensitivities from 33 to 100 % in 11 studies [34], with lower sensitivities associated with low-grade tumors, presumably due to lower levels of enhancement reflecting weaker angiogenesis.

DCIS

With improved technique and higher spatial resolution, MRI has become increasingly sensitive for detecting both calcified and noncalcified DCIS [35–38]. Detection is particularly improved in intermediate- to high-grade tumors [22, 37, 39]. Given the challenge of diagnosing DCIS and high rates of re-excision, accurate assessment of extent of disease is vital in these patients. Although more accurate size estimation of DCIS by MRI over mammography and ultrasound has not be consistently established in the literature [3, 22–24, 39, 40], there is evidence that MRI improves lesion size assessment over mammography, particularly in high-grade DCIS.

Patients with DCIS may benefit from preoperative MRI for the detection of an invasive tumor component not demonstrated at the time of biopsy, which has important staging, treatment, and prognostic implications. In several studies, MRI outperformed mammography in the detection of occult invasive component in DCIS [40–43], with greater sensitivities associated with larger lesion size and the presence of a mass [41, 44]. On the other hand, the absence of occult invasion on breast MRI has a high negative predictive value and helps confirm preoperative staging in a patient with DCIS.

Detection of Additional Disease

Preoperative MRI has consistently demonstrated high diagnostic accuracy in visualizing otherwise occult sites of disease, including multifocal, multicentric, and contralateral involvement [16–19]. In a meta-analysis including 2610 patients, MRI detected additional tumors in 16 % of patients, resulting in a change in surgical management in 11 % [16]. A larger meta-analysis by Plana et al. included 10,811 patients from 50 studies, found even higher rates of additional disease detection in 20 % of patients [17]. The detection of additional contralateral breast cancer was also reported in an average 5.5 % of patients [17]. The diagnosis of additional suspicious findings on MRI usually require tissue sampling to confirm disease extent, which in turn, dictate the ultimate surgical and medical treatment planning.

Assessment of Chest Wall, Nipple, and Skin Involvement

Posterior

MRI is an excellent modality in assessing chest wall involvement by a posterior tumor. This is possible given superior anatomic detail and contrast enhancement of the posterior breast to the level of the chest wall encompassed in the field of view. Invasion is indicated by infiltration and abnormal enhancement of underlying musculature and not simply by

violation of the fat planes, a distinction readily made by MRI [45]. Pectoralis muscle invasion, while it does not change the tumor staging by TNM classification, affects surgical approach. Chest wall invasion, defined as involvement of the ribs or chest wall musculature (serratus anterior and intercostal muscles), does alter staging, prognosis, and treatment.

Anterior

MRI is helpful in assessing disease involvement of the nipple-areolar complex (NAC) for similar reasons previously stated. While involvement of the NAC on MRI does not necessarily change tumor staging, it alters surgical planning and precludes the patient from nipple-sparing mastectomy. MRI has been shown to be useful in determining NAC involvement in multiple studies [46–49]. The involvement of the NAC on MRI manifests in asymmetric nipple enhancement contiguous with enhancement from index tumor [47], or in proximity of index tumor to the NAC (within 2 cm, range 5 mm–2 cm) without direct nipple enhancement [48, 49]. Similarly, MRI is helpful in detecting skin involvement (in non-inflammatory cancers), which appears as localized skin thickening and enhancement contiguous to the index tumor. This however requires clinical correlation of local skin ulceration or nodule on physical exam, and diagnosis requires skin punch biopsy. Direct skin invasion upgrades disease to at least stage IIIB and portends poor prognosis.

Nodal Evaluation

The detection of lymph node involvement affects staging, treatment, and prognosis in breast cancer patients. The ability to accurately exclude axillary nodal disease preoperatively helps spare patients from the morbidity associated with axillary lymph node dissection (ALND). While ultrasound is traditionally the mainstay for evaluating axillary nodal involvement, it is operator dependent and unable to consistently assess higher axillary nodal levels II and III, supraclavicular and internal mammary lymph nodes, which are better visualized and more consistently assessed by MRI given its wider field of view. Adding MRI to ultrasound has been found to reduce false negative rate, and increase negative predictive value (98 %) in evaluating level III axillary nodes (infraclavicular nodes), supraclavicular nodes, and internal mammary nodes [50].

MRI allows for the assessment of morphologic, signal intensity, and enhancement characteristics, which can help differentiate benign from metastatic lymph nodes. Features of pathologic lymph nodes on MRI include irregular nodal contour, high T2-weighted signal intensity, marked gadolinium enhancement, round fatty hila, and abnormal cortices [51]. A prospective study of 65 patients with invasive breast cancer found that early contrast enhancement, as defined by an increase in signal intensity of >100 % on the first post contrast image obtained at 57 s after injection, was found to be both sensitive (83 %) and specific (90 %) for the detection of metastatic nodal involvement [52]. Quantitative features such as diffusion-weighted imaging (DWI) and dynamic contrast enhancement (DCE) are of questionable additional value in distinguishing benign from malignant lymph nodes [53, 54]. Fine needle aspiration and ultimately sentinel lymph node dissection (SLND) help further assess nodal involvement.

The traditional preoperative determination of axillary nodal involvement prompting axillary lymph node dissection (ALND) has been called into question by the American College of Surgeons Oncology Group (ACOSOG) Z0011 trial [55], which found no benefit in performing ALND in patients with early stage T1/T2 invasive cancers and one or two positive sentinel lymph nodes treated with chemoradiation therapy, as compared to SLND. The implications of these results have been debated, and the short study follow-up (median 6.3 years) and small sample size have been criticized. Despite this controversy, because ALND does not routinely include higher axillary level II/III nodes, or internal mammary and supraclavicular nodes, MRI remains an important diagnostic tool in preoperative staging. Involvement of internal mammary and supraclavicular lymph nodes may not change surgical planning, but will alter radiation treatment parameters.

Controversies of Breast MR in Locoregional Disease Staging

While superior sensitivity and diagnostic accuracy of MR are well established, improvement in clinical outcomes associated with preoperative MR is less clear.

Positive Margins and Re-excision Rates

Surgical margins positive for tumor indicate failure of initial surgical excision to include the entire extent of disease, necessitating re-excision. The primary aim of a preoperative MRI is to improve disease extent assessment, allowing for better initial surgical success, thus minimizing re-excision. While preoperative MRI has been shown to alter surgical management [3, 56–58], there are mixed results on its impact on re-excision rates (Table 1). Multiple prior studies including two prospective trials (MONET and COMICE) showed preoperative MRI did not reduce re-excision rate. The MONET (MR mammography of non-palpable breast tumors) trial from the Netherlands included 418 patients with nonpalpable breast cancers diagnosed on mammography and ultrasound. This study showed an unexpectedly increased re-excision rate in patients with MRI (34 %) vs those without MRI (12 %) [64]. However, surgical bias in this study (wider surgical excision in

Table 1 Impact of preoperative MRI on surgical outcomes based on index lesion histology

	Study	Type of study	No. of MRI patients/total	Re-excision with MRI	Re-excision without MRI	*P* value	Initial mastectomy with MRI	Initial mastectomy without MRI	*P* value	Conversion to mastectomy with MRI	Conversion to mastectomy without MRI	*P* value	Summary
Invasive lobular cancer	McGhan 2010 [59]	Retro	70/178	4.2 %	9.2 %	0.2	31.9 %	23.9 %	0.23	2.8 %	7.3 %	0.189	Decreased re-excision rates; no significant effect on mastectomy rates
	Mann 2010 [86]	Retro	99/267	5.0 %	14.9 %	0.01	45 %	46 %	0.753	7 %	23 %	0.013	
	Heil 2011 [60]	Retro	92/178	11.3 %	9.0 %	0.32	37.7 %	30.3 %	0.12	8 %	9 %	0.401	
	Houssami 2013 [25]	Meta	417/766	10.9 %	18.0 %	0.031	31.1 %	24.9 %	0.056	12.4 %	16.4 %	0.22	
	Fortune-Greeley 2014 [61•]	Retro	396/1928	25.3 %	29.1 %	0.21	33.1 %	35.5 %	0.37	–	–	–	
All histologies	Bleicher 2009 [62]	Retro	130/577	–	–	–	27.7 %	19.9 %	0.024	9.8 %	5.9 %	0.35	Equivocal impact on re-excision rates; increased initial mastectomy rates
	Turnbull 2010 [63] (COMICE)	RCT	816/1623	18.8 %	19.3 %	0.769	–	–	–	–	–	–	
	Peters 2011 [64] (MONET)	RCT	207/418	34 %	12 %	0.008	–	–	–	11 %	14 %	0.49	
	Houssami 2013 [25]	Meta	1802/3112	11.6 %	11.4 %	0.71	16.4 %	8.1 %	<0.001	6.0 %	7.3 %	0.23	
	Gonzalez 2014 [65•]	RCT	220/440	5 %	15 %	<0.001	–	–	–	20 %	10 %	0.024	
	Chandwani 2014 [66]	Retro	304/609	18.1 %	20.3 %	0.484	38.2 %	33.1 %	0.194	–	–	–	
	Patel 2015 [67]	Retro	96/250	7.1 %	25.0 %	<0.001	51.3 %	40.6 %	0.1	–	–	–	
	Fancellu 2015[a] [68]	Meta	1077/3252	41.6 %	40.1 %	0.759	27.6 %	18.2 %	0.012	13.9 %	11.5 %	0.340	

Retro retrospective study, *Meta* meta-analysis, *RCT* randomized control trial

[a] Meta-analysis including only patients with DCIS

patients without MRI compared to those with MRI) may have masked any benefit from MRI, and could potentially account for the paradoxically increased re-excision rate. The COMICE (Comparative Effectiveness of MRI in Breast Cancer) trial, a multicenter study that included 1623 patients from the UK, also demonstrated no reduction in re-excision rate with preoperative MRI [63]. This study was performed before MRI-guided localization and biopsy were routinely available, and not all suspicious findings were biopsied prior to excision, therefore likely overdiagnosing the need for additional surgery [33]. Moreover, very wide surgical excisions routinely implemented in the UK as a result of national benchmark for low re-excision rates (mandated to fall below 10 %) likely masked any potential benefit of preoperative MRI.

Recent studies have shown more favorable results, demonstrating deceased re-excision rates with preoperative MRI [65•, 67, 69–71], while other studies continue to show the contrary [62, 68]. The inconsistencies in the data are confounded by surgical bias, which is a major challenge in breast imaging research, highlighting the need for standardization and collaboration across specialties.

Mastectomy Rates

Preoperative MRI has been shown to be correlated with an increased rate of mastectomy in multiple studies [17, 25, 26, 62, 65•, 66], including in a meta-analysis of 3112 patients with all histologic types of breast cancer which showed increased initial and overall mastectomy rate in those who underwent preoperative MRI [25] (Table 1). The upward trend of mastectomy in patients diagnosed with breast cancer, however, is not attributed to preoperative MRI alone. There is evidence that multiple other factors such as improved ability to identify high-risk women, better understanding of post radiation changes, further advancement in oncoplastic techniques allowing superior cosmetic results, and patient empowerment and choice, all contribute to the decision to choose mastectomy [72]. In addition, there is evidence that in the setting of preoperative MRI diagnosing additional foci of disease, the majority of surgical conversion from BCT to mastectomy is appropriate (8.3 %) [17] versus inappropriate based on false-positive findings (1.1–1.7 %) [16, 17].

Overestimation of Disease

Although the majority of the existing literature supports high accuracy of MRI in tumor size estimation, several studies have demonstrated a tendency of MRI to overestimate disease [3, 4, 6, 22–24]. Berg et al. found that the addition of MRI to preoperative planning resulted in overestimation of extend of disease in 21 % of cases, compared to 3.1 % cases with clinical breast exam (CBE) and mammography, and 12 % with CBE, mammography, and ultrasound [3]. This is not entirely

unexpected, given high sensitivity but moderate specificity of MRI. Overestimation may be due to enhancement of a number of benign structures such as normal surrounding fibroglandular tissue, fibrocystic disease, or fat necrosis [73]. Tumor size overestimation has been shown to be more common in larger tumors (size >2 cm) [4, 6], and less common in high-grade tumors [13, 37, 39, 74]. The possibility of disease overestimation on MRI underscores the importance of tissue sampling for confirmation. Although additional potentially unnecessary biopsies are associated with unintended negative psychosocial stigma, MRI remains highly effective in excluding significant disease (high negative predictive value).

Recurrence and Disease-Free Survival

Actual implications of having a preoperative MRI on breast cancer patient prognosis and long-term survival are much less clear. The effect of preoperative MRI on recurrence rates and overall disease-free survival has not been well established in the literature due to a lack of long-term outcome data (Table 2). A recent meta-analysis by Houssami et al. showed that preoperative MRI did not affect local or distant recurrence rates [76•]. Other recent retrospective studies [71, 75, 77, 78] yielded similar results. A study of 2321 women with DCIS found that the use of MRI afforded no benefit in long-term locoregional recurrence or in the development of contralateral cancer at 8 years [77]. The lack of demonstrable survival benefits may in part reflect the fact that small volume additional disease detected on MRI may be adequately treated by whole-breast radiation therapy (WBRT) following BCT with or without MRI.

Other more recent studies have suggested that preoperative MRI provided a benefit in recurrence rate and disease-free survival, including a study of 398 patients with early-stage triple-negative breast cancers, which found that the absence of preoperative MRI was associated with an increased risk of recurrence [79, 80]. In particular, there is evidence that contralateral breast cancer recurrence is reduced with MRI [78, 80].

Treatment Delay

Performing preoperative MRI may delay definitive treatment. Studies reported significant treatment delay of 12.2 to 22.4 days due to additional workup prompted by preoperative MRI [57, 62, 66]. On the other hand, a smaller retrospective study of 147 patients out of Ontario found no significant delay in treatment as a result of preoperative MRI [57]. The authors contributed the lack of delay to prompt performance of the MRI and post MRI workup in accordance with maximum wait time benchmarks set by the Ministry of Health. Similarly, prompt workup should be the goal of any facility offering preoperative MRI to minimize harm, reduce patient anxiety, reduce cost, and optimize care.

Subgroups Most Likely to Benefit From a Preoperative Breast MR

Invasive Lobular Cancer

Invasive lobular cancer (ILC) is relatively occult on mammography due to its lepidic growth pattern, and associated with increased incidence of multifocal and contralateral disease [58, 59, 81–84]. MRI has shown improved sensitivity and superior tumor size estimation over clinical breast exam, mammography, and ultrasound for ILC. MRI is particularly beneficial in the ILC group in detecting additional foci of disease, both in the ipsilateral and in the contralateral breast [18, 83–85]. In turn, changes in surgical management based on preoperative MRI findings have been greater in ILC than in other histologic subtypes [56, 58, 83, 84]. Overall surgical outcomes in ILC are improved by performing a preoperative MRI. Whereas data on re-excision rates are equivocal for all histologic types, multiple studies have shown lower re-excision rates in ILC following BCT [25, 59, 61•, 86]. However, the detection of more foci of disease by MRI seems to be associated with a higher rates of initial mastectomy as more patients are found not to be candidates for BCT [25, 60]. Although the data for diagnostic accuracy and clinical outcomes are still not unanimous, overall findings suggest preoperative MRI to be of benefit in the setting of ILC.

Occult Primary Breast Cancer

In the rare instance that axillary nodal metastasis presents without clinical or imaging evidence of primary tumor, patients may ultimately undergo axillary lymph node dissection with mastectomy or whole-breast radiation (WBRT). MRI has an important role in diagnostic workup in these patients, as the identification of a primary tumor may allow for conversion to BCT. A meta-analysis by de Bresser, et al. reviewed 8 studies including 220 women with occult breast cancer [87]. Overall, MRI was able to identify a suspicious lesion in an average of 72 % of patients, yielding an overall sensitivity of 90 %. However, as in other clinical settings, specificity of MRI was considerably lower at 31 %, highlighting the utility of MRI as a negative predictive study [87]. The successful identification of an otherwise occult primary cancer allowed for the conversion to BCT in an average of 35 % of women.

Elevated Risk Patients

Patients at elevated risks for breast cancer, including those with genetic mutations, personal and family history of breast cancer, and childhood chest radiation, may benefit from a

Table 2 Impact of preoperative MRI on locoregional recurrence and disease-free survival

Study	Type of study	No MRI/total	Path of index lesion	Length of follow-up (years)	LRR with MRI	LRR without MRI	*P* value	Disease-free survival benefit of MRI (*P* value)[b]	Summary
Ko 2013 [75]	Retro	229/615	Invasive or in situ	5.7	6.1 %	6.3 %	1.0	–	Equivocal impact on locoregional recurrence and disease free survival
Houssami 2014 [76•]	Meta	1347/3169	Invasive or in situ	2.9	1.8 %	2.2 %	0.88	0.87	
Sung 2014 [71]	Retro	174/348	Invasive or in situ	8	12 %	17 %	0.33	0.73	
Pilewskie 2014 [77]	Retro	596/2321	DCIS	4.9	8.5 %	7.2 %	0.52	–	
Yi 2015 [78]	Retro	97/194[a]	Invasive or in situ	6.1	3.1 %	4.1 %	0.18	<0.001**	
Bae 2015 [79]	Retro	345/398	Invasive	6.1	13.6 %	30.1 %	0.006	<0.001	

Retro retrospective study, *Meta* meta-analysis, *LRR* locoregional recurrence

[a] Data presented from bilateral MRI imaging period

[b] Based on Kaplan- Meier survival analysis

**Disease-free survival benefit due to reduction in contralateral disease recurrence

preoperative MRI, as they have a higher rate of synchronous ipsilateral and contralateral disease [18, 19, 88]. A prospective study by Lehman et al. of 171 elevated risk women who underwent screening mammography, US and MRI found that MRI had a higher diagnostic yield than mammography and US (3.5 % versus 1.2 % and 0.6 %, respectively), but also prompted a higher biopsy rate [89]. Additional studies confirmed the added sensitivity of MRI over other modalities in high/moderate risk surveillance [31, 90, 91]. While these studies included asymptomatic women in a screening setting, they highlighted the increased sensitivity of MRI in this group of patients. Importantly, there is no current evidence to show that the improved diagnostic performance of MRI in this setting results in a survival benefit.

Dense Breasts

Mammographic breast density has been established as an independent marker for breast cancer risk [92, 93]. As in other groups of elevated risk patients as previously discussed, much of the data on MRI is derived from screening data such as the ACRIN (American College of Radiology Imaging Network) 6666 trial [94]. This multicenter study included 2809 high risk patients with dense breasts and found that the additional of MRI to screening mammogram and ultrasound provided a supplemental caner yield of 14.7 cancers per 1000 screened, but also resulted in a higher false-positive rate. As a result of such screening data, dense breast legislation enacted in several states recommends the addition of screening ultrasound or MRI for women with dense breasts. Similarly, in studies of patients with previously diagnosed breast cancer, MRI provides increased detection sensitivity and identification of additional foci of disease over mammography in patients with dense breast tissue [3, 7, 95].

Partial Breast Irradiation Candidacy

Standard protocol for BCT includes whole-breast radiation (WBRT) following lumpectomy. In select patients, partial breast irradiation (PBI) may be offered as an alternative regimen. The American Society for Radiation Oncology defines a "suitable" candidate for PBI as a patient with a small unifocal unicentric tumor (<2 cm) [96]. PBI offers the benefit of limiting nontarget radiation to adjacent organs such as the heart and lung and minimizes the time course of treatment to 5 days as compared to the standard 5–6 weeks required for WBRT. Since PBI only treats a portion of the breast tissue at the site of the primary tumor, lack of additional disease must be established to ensure adequate treatment. Given high sensitivity and high negative predictive value, MRI is the perfect test to confirm unifocal disease in a PBI candidate. A prospective study by Dorn et al. of 521 patients found preoperative MRI changed eligibility in 13 % of patients screened for PBI,

suggesting MRI to be an important step in preoperative assessment to establish PBI candidacy [97].

Conclusions

Breast MRI is superior in assessing tumor size and extent, optimizing treatment planning. Although the role of MRI in routine preoperative assessment of newly diagnosed breast cancer is not entirely clear, it has been shown to be of benefit in certain subgroups of women. While current data on preoperative MRI do not show a benefit in decreasing repeat surgery or increasing survival, more positive results have emerged in recent studies, and further data is needed. Meanwhile, the decision of whether or not to pursue a preoperative MRI continues to be one made on a patient by patient basis.

Compliance with Ethical Standards

Conflict of Interest Marissa Albert, Yiming Gao, and Linda Moy declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

References

Papers of particular interest, published recently, have been highlighted as:
• Of importance

1. Stout NK, Nekhlyudov L, Li L, et al. Rapid increase in breast magnetic resonance imaging use: trends from 2000 to 2011. JAMA Intern Med. 2014;174(1):114–21.
2. Bassett LW, Dhaliwal SG, Eradat J, et al. National trends and practices in breast MRI. Am J Roentgenol. 2008;191(2):332–9.
3. Berg WA, Gutierrez L, NessAiver MS, et al. Diagnostic accuracy of mammography, clinical examination, US, and MR imaging in preoperative assessment of breast cancer 1. Radiology. 2004;233(3):830–49.
4. Onesti JK, Mangus BE, Helmer SD, Osland JS. Breast cancer tumor size: correlation between magnetic resonance imaging and pathology measurements. Am J Surg. 2008;196(6):844–50.
5. Luparia A, Mariscotti G, Durando M, et al. Accuracy of tumour size assessment in the preoperative staging of breast cancer: comparison of digital mammography, tomosynthesis, ultrasound and MRI. Radiol Med. 2013;118(7):1119–36.
6. Jethava A, Ali S, Wakefield D, Crowell R, Sporn J, Vrendenburgh J. Diagnostic accuracy of MRI in predicting breast tumor size: comparative analysis of MRI vs histopathological assessed breast tumor size. Conn Med. 2015;79(5):261.
7. Van Goethem M, Schelfout K, Dijckmans L, et al. MR mammography in the pre-operative staging of breast cancer in patients with dense breast tissue: comparison with mammography and ultrasound. Eur Radiol. 2004;14(5):809–16.
8. Kim WH, Chang JM, Moon H-G, et al. Comparison of the diagnostic performance of digital breast tomosynthesis and magnetic resonance imaging added to digital mammography in women with known breast cancers. Eur Radiol. 2015:1-9.
9. Hollingsworth AB, Stough RG, O'Dell CA, Brekke CE. Breast magnetic resonance imaging for preoperative locoregional staging. Am J Surg. 2008;196(3):389–97.
10. Mercier J, Kwiatkowski F, Abrial C, et al. The role of tomosynthesis in breast cancer staging in 75 patients. Diagn Interv Imaging. 2015;96(1):27–35.
11. Schnall MD, Blume J, Bluemke DA, et al. MRI detection of distinct incidental cancer in women with primary breast cancer studied in IBMC 6883. J Surg Oncol. 2005;92(1):32–8.
12. Van Goethem M, Schelfout K, Kersschot E, et al. MR mammography is useful in the preoperative locoregional staging of breast carcinomas with extensive intraductal component. Eur J Radiol. 2007;62(2):273–82.
13. Schouten van der Velden A, Boetes C, Bult P, Wobbes T. Magnetic resonance imaging in size assessment of invasive breast carcinoma with an extensive intraductal component. BMC Med Imaging. 2009;2009:5.
14. Hata T, Takahashi H, Watanabe K, et al. Magnetic resonance imaging for preoperative evaluation of breast cancer: a comparative study with mammography and ultrasonography. J Am Coll Surg. 2004;198(2):190–7.
15. Lehman CD, DeMartini W, Anderson BO, Edge SB. Indications for breast MRI in the patient with newly diagnosed breast cancer. J Natl Compr Cancer Netw. 2009;7(2):193–201.
16. Houssami N, Ciatto S, Macaskill P, et al. Accuracy and surgical impact of magnetic resonance imaging in breast cancer staging: systematic review and meta-analysis in detection of multifocal and multicentric cancer. J Clin Oncol. 2008;26(19):3248–58.
17. Plana MN, Carreira C, Muriel A, et al. Magnetic resonance imaging in the preoperative assessment of patients with primary breast cancer: systematic review of diagnostic accuracy and meta-analysis. Eur Radiol. 2012;22(1):26–38.
18. Liberman L, Morris EA, Dershaw DD, Abramson AF, Tan LK. MR imaging of the ipsilateral breast in women with percutaneously proven breast cancer. Am J Roentgenol. 2003;180(4):901–10.
19. Liberman L, Morris EA, Kim CM, et al. MR imaging findings in the contralateral breast of women with recently diagnosed breast cancer. Am J Roentgenol. 2003;180(2):333–41.
20. El Khouli RH, Jacobs MA, Macura KJ. Breast MRI for diagnosis and staging of breast cancer. Breast Cancer Screen Diagn Springer. 2015;2015:181–200.
21. DeMartini W, Lehman C, Partridge S. Breast MRI for cancer detection and characterization: a review of evidence-based clinical applications. Acad Radiol. 2008;15(4):408–16.
22. Kropcho LC, Steen ST, Chung AP, Sim MS, Kirsch DL, Giuliano AE. Preoperative breast MRI in the surgical treatment of ductal carcinoma in situ. Breast J. 2012;18(2):151–6.
23. Pilewskie M, Kennedy C, Shappell C, et al. Effect of MRI on the management of ductal carcinoma in situ of the breast. Ann Surg Oncol. 2013;20(5):1522–9.
24. van der Velden APS, Boetes C, Bult P, Wobbes T. The value of magnetic resonance imaging in diagnosis and size assessment of in situ and small invasive breast carcinoma. Am J Surg. 2006;192(2):172–8.
25. Houssami N, Turner R, Morrow M. Preoperative magnetic resonance imaging in breast cancer: meta-analysis of surgical outcomes. Ann Surg. 2013;257(2):249–55.
26. Itakura K, Lessing J, Sakata T, et al. The impact of preoperative magnetic resonance imaging on surgical treatment and outcomes for ductal carcinoma in situ. Clin Breast Cancer. 2011;11(1):33–8.

27. Mann RM, Kuhl CK, Kinkel K, Boetes C. Breast MRI: guidelines from the European society of breast imaging. Eur Radiol. 2008;18(7):1307–18.
28. Position statement on the use of magnetic resonance imaging in breast surgical oncology. https://www.breastsurgeons.org/statements/PDF_Statements/MRI.pdf: The American Society of Breast Surgeons; 2010.
29. ACR practive parameter for the performance of contrast-enhanced magnetic resonance imaging (MRI) of the breast. Pract Parameter. http://www.acr.org/~/media/2a0eb28eb59041e2825179afb72ef624.pdf: American College of Radiology; 2014.
30. Sardanelli F, Boetes C, Borisch B, et al. Magnetic resonance imaging of the breast: recommendations from the EUSOMA working group. Eur J Cancer. 2010;46(8):1296–316.
31. Kuhl CK, Schrading S, Leutner CC, et al. Mammography, breast ultrasound, and magnetic resonance imaging for surveillance of women at high familial risk for breast cancer. J Clin Oncol. 2005;23(33):8469–76.
32. Rahbar H, DeMartini WB, Lee AY, Partridge SC, Peacock S, Lehman CD. Accuracy of 3T versus 1.5 T breast MRI for preoperative assessment of extent of disease in newly diagnosed DCIS. Eur J Radiol. 2015;84(4):611–6.
33. Brasic N, Wisner DJ, Joe BN. Breast MR imaging for extent of disease assessment in patients with newly diagnosed breast cancer. Magn Reson Imaging Clin N Am. 2013;21(3):519–32.
34. van der Velden APS, Schlooz-Vries MS, Boetes C, Wobbes T. Magnetic resonance imaging of ductal carcinoma in situ: what is its clinical application? A review. Am J Surg. 2009;198(2):262–9.
35. Mossa-Basha M, Fundaro GM, Shah BA, Ali S, Pantelic MV. Ductal carcinoma in situ of the breast: MR imaging findings with histopathologic correlation 1. Radiographics. 2010;30(6):1673–87.
36. Harms SE. The use of breast magnetic resonance imaging in ductal carcinoma in situ. Breast J. 2005;11(6):379–81.
37. Kuhl CK, Schrading S, Bieling HB, et al. MRI for diagnosis of pure ductal carcinoma in situ: a prospective observational study. Lancet. 2007;370(9586):485–92.
38. Lehman CD. Magnetic resonance imaging in the evaluation of ductal carcinoma in situ. J Natl Cancer Inst Monogr. 2009;2010(41):150–1.
39. Kim DY, Moon WK, Cho N, et al. MRI of the breast for the detection and assessment of the size of ductal carcinoma in situ. Korean J Radiol. 2007;8(1):32–9.
40. Deurloo EE, Sriram JD, Teertstra HJ, et al. MRI of the breast in patients with DCIS to exclude the presence of invasive disease. Eur Radiol. 2012;22(7):1504–11.
41. Goto M, Yuen S, Akazawa K, et al. The role of breast MR imaging in pre-operative determination of invasive disease for ductal carcinoma in situ diagnosed by needle biopsy. Eur Radiol. 2012;22(6):1255–64.
42. Hollingsworth AB, Stough RG. Multicentric and contralateral invasive tumors identified with pre-op MRI in patients newly diagnosed with ductal carcinoma in situ of the breast. Breast J. 2012;18(5):420–7.
43. Hwang ES, Kinkel K, Esserman LJ, Lu Y, Weidner N, Hylton NM. Magnetic resonance imaging in patients diagnosed with ductal carcinoma-in-situ: value in the diagnosis of residual disease, occult invasion, and multicentricity. Ann Surg Oncol. 2003;10(4):381–8.
44. Huang Y-T, Cheung Y-C, Lo Y-F, Ueng S-H, Kuo W-L, Chen S-C. MRI findings of cancers preoperatively diagnosed as pure DCIS at core needle biopsy. Acta Radiol. 2011;52(10):1064–8.
45. Morris EA, Schwartz LH, Drotman MB, et al. Evaluation of pectoralis major muscle in patients with posterior breast tumors on breast MR images: early experience 1. Radiology. 2000;214(1):67–72.
46. Moon JY, Chang Y-W, Lee EH, Seo DY. Malignant invasion of the nipple-areolar complex of the breast: usefulness of breast MRI. Am J Roentgenol. 2013;201(2):448–55.
47. Sakamoto N, Tozaki M, Hoshi K, Fukuma E. Is MRI useful for the prediction of nipple involvement? Breast Cancer. 2013;20(4):316–22.
48. Ponzone R, Maggiorotto F, Carabalona S, et al. MRI and intraoperative pathology to predict nipple–areola complex (NAC) involvement in patients undergoing NAC-sparing mastectomy. Eur J Cancer. 2015;51(14):1882–9.
49. Steen ST, Chung AP, Han S-H, Vinstein AL, Yoon JL, Giuliano AE. Predicting nipple–areolar involvement using preoperative breast MRI and primary tumor characteristics. Ann Surg Oncol. 2013;20(2):633–9.
50. Hyun S, Kim E-K, Yoon J, Moon H, Kim M. Adding MRI to ultrasound and ultrasound-guided fine-needle aspiration reduces the false-negative rate of axillary lymph node metastasis diagnosis in breast cancer patients. Clin Radiol. 2015;70:716–22.
51. Luciani A, Dao TH, Lapeyre M, et al. Simultaneous bilateral breast and high-resolution axillary MRI of patients with breast cancer: preliminary results. Am J Roentgenol. 2004;182(4):1059–67.
52. Kvistad K, Rydland J, Smethurst H-B, Lundgren S, Fjøsne H, Haraldseth O. Axillary lymph node metastases in breast cancer: preoperative detection with dynamic contrast-enhanced MRI. Eur Radiol. 2000;10(9):1464–71.
53. Rahbar H, Conlin JL, Parsian S, et al. Suspicious axillary lymph nodes identified on clinical breast MRI in patients newly diagnosed with breast cancer: can quantitative features improve discrimination of malignant from benign? Acad Radiol. 2015;22(4):430–8.
54. Rautiainen S, Kononen M, Sironen R, et al. Preoperative axillary staging with 3.0-T breast MRI: clinical value of diffusion imaging and apparent diffusion coefficient. PLoS One. 2015;10(3):e0122516.
55. Giuliano AE, McCall L, Beitsch P, et al. Locoregional recurrence after sentinel lymph node dissection with or without axillary dissection in patients with sentinel lymph node metastases: the American College of Surgeons Oncology Group Z0011 randomized trial. Ann Surg. 2010;252(3):426–33.
56. Bedrosian I, Mick R, Orel SG, et al. Changes in the surgical management of patients with breast carcinoma based on preoperative magnetic resonance imaging. Cancer. 2003;98(3):468–73.
57. Angarita FA, Acuna SA, Fonseca A, Crystal P, Escallon J. Impact of preoperative breast MRIs on timing of surgery and type of intervention in newly diagnosed breast cancer patients. Ann Surg Oncol. 2010;17(3):273–9.
58. Kneeshaw P, Turnbull L, Smith A, Drew P. Dynamic contrast enhanced magnetic resonance imaging aids the surgical management of invasive lobular breast cancer. Eur J Surg Oncol. 2003;29(1):32–7.
59. McGhan LJ, Wasif N, Gray RJ, et al. Use of preoperative magnetic resonance imaging for invasive lobular cancer: good, better, but maybe not the best? Ann Surg Oncol. 2010;17(3):255–62.
60. Heil J, Bühler A, Golatta M, et al. Does a supplementary preoperative breast MRI in patients with invasive lobular breast cancer change primary and secondary surgical interventions? Ann Surg Oncol. 2011;18(8):2143–9.
61.• Fortune-Greeley AK, Wheeler SB, Meyer A-M, et al. Preoperative breast MRI and surgical outcomes in elderly women with invasive ductal and lobular carcinoma: a population-based study. Breast Cancer Res Treat. 2014;143(1):203–12. **This population based study of patients with early stage breast cancer found that preoerative MRI reduced excision rates in patients with invasive lobular cancer without affecting final mastectomy rates. Overall, and in patients with invasive ductal histology, there was no reduction in re-excision rates and an increase in final mastectomy rates**.

62. Bleicher RJ, Ciocca RM, Egleston BL, et al. Association of routine pretreatment magnetic resonance imaging with time to surgery, mastectomy rate, and margin status. J Am Coll Surg. 2009;209(2):180–7.
63. Turnbull LW, Brown SR, Olivier C, et al. Multicentre randomised controlled trial examining the cost-effectiveness of contrast-enhanced high field magnetic resonance imaging in women with primary breast cancer scheduled for wide local excision (COMICE). Health Technol Assess. 2010;14(1):1–182.
64. Peters N, Van Esser S, van den Bosch M, et al. Preoperative MRI and surgical management in patients with nonpalpable breast cancer: the MONET-randomised controlled trial. Eur J Cancer. 2011;47(6):879–86.
65.• 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):1685–93. **This prospective, randomized, multicneter study demostated a significant reduction in reoperation rates in patients with preoperative MRI. Conversion to mastectomy from breast conservation was also higher in those with preoperative MRI, though final mastectomy rates were not significantly different**.
66. Chandwani S, George PA, Azu M, et al. Role of preoperative magnetic resonance imaging in the surgical management of early-stage breast cancer. Ann Surg Oncol. 2014;21(11):3473–80.
67. Patel BK, Shah NA, Galgano SJ, et al. Does preoperative MRI workup affect mastectomy rates and/or re-excision rates in patients with newly diagnosed breast carcinoma? A retrospective review. Breast J. 2015;21(6):604–9.
68. Fancellu A, Turner RM, Dixon JM, Pinna A, Cottu P, Houssami N. Meta-analysis of the effect of preoperative breast MRI on the surgical management of ductal carcinoma in situ. Br J Surg. 2015;102:883–93.
69. Grady I, Gorsuch-Rafferty H, Hadley P. Preoperative staging with magnetic resonance imaging, with confirmatory biopsy, improves surgical outcomes in women with breast cancer without increasing rates of mastectomy. Breast J. 2012;18(3):214–8.
70. Obdeijn I-M, Tilanus-Linthorst MM, Spronk S, et al. Preoperative breast MRI can reduce the rate of tumor-positive resection margins and reoperations in patients undergoing breast-conserving surgery. Am J Roentgenol. 2013;200(2):304–10.
71. Sung JS, Li J, Da Costa G, et al. Preoperative breast MRI for early-stage breast cancer: effect on surgical and long-term outcomes. Am J Roentgenol. 2014;202(6):1376–82.
72. Balch CM, Jacobs LK. Mastectomies on the rise for breast cancer: "the tide is changing". Ann Surg Oncol. 2009;16(10):2669–72.
73. Van Goethem M, Tjalma W, Schelfout K, Verslegers I, Biltjes I, Parizel P. Magnetic resonance imaging in breast cancer. Eur J Surg Oncol. 2006;32(9):901–10.
74. Marcotte-Bloch C, Balu-Maestro C, Chamorey E, et al. MRI for the size assessment of pure ductal carcinoma in situ (DCIS): a prospective study of 33 patients. Eur J Radiol. 2011;77(3):462–7.
75. Ko ES, Han BK, Kim RB, et al. Analysis of the effect of breast magnetic resonance imaging on the outcome in women undergoing breast conservation surgery with radiation therapy. J Surg Oncol. 2013;107(8):815–21.
76.• Houssami N, Turner R, Macaskill P, et al. An individual person data meta-analysis of preoperative magnetic resonance imaging and breast cancer recurrence. J Clin Oncol. 2014. doi:10.1200/JCO.2013.52.7515. **This meta-analysis showed that preoperative MRI did not reduce the rates of local or distant recurrence**.
77. Pilewskie M, Olcese C, Eaton A, et al. Perioperative breast MRI is not associated with lower locoregional recurrence rates in DCIS patients treated with or without radiation. Ann Surg Oncol. 2014;21(5):1552–60.
78. Yi A, Cho N, Yang K-S, Han W, Noh D-Y, Moon WK. Breast cancer recurrence in patients with newly diagnosed breast cancer without and with preoperative MR imaging: a matched cohort study. Radiology. 2015. doi:10.1148/radiol.2015142101.
79. Bae MS, Moon H-G, Han W, et al. Early stage triple-negative breast cancer: imaging and clinical-pathologic factors associated with recurrence. Radiology. 2015. doi:10.1148/radiol.2015150089.
80. Fischer U, Zachariae O, Baum F, von Heyden D, Funke M, Liersch T. The influence of preoperative MRI of the breasts on recurrence rate in patients with breast cancer. Eur Radiol. 2004;14(10):1725–31.
81. Boetes C, Veltman J, van Die L, Bult P, Wobbes T, Barentsz JO. The role of MRI in invasive lobular carcinoma. Breast Cancer Res Treat. 2004;86(1):31–7.
82. Brem RF, Ioffe M, Rapelyea JA, et al. Invasive lobular carcinoma: detection with mammography, sonography, MRI, and breast-specific gamma imaging. Am J Roentgenol. 2009;192(2):379–83.
83. Caramella T, Chapellier C, Ettore F, Raoust I, Chamorey E, Balu-Maestro C. Value of MRI in the surgical planning of invasive lobular breast carcinoma: a prospective and a retrospective study of 57 cases: comparison with physical examination, conventional imaging, and histology. Clin Imaging. 2007;31(3):155–61.
84. Mann RM, Hoogeveen YL, Blickman JG, Boetes C. MRI compared to conventional diagnostic work-up in the detection and evaluation of invasive lobular carcinoma of the breast: a review of existing literature. Breast Cancer Res Treat. 2008;107(1):1–14.
85. Schelfout K, Van Goethem M, Kersschot E, et al. Preoperative breast MRI in patients with invasive lobular breast cancer. Eur Radiol. 2004;14(7):1209–16.
86. Mann RM, Loo CE, Wobbes T, et al. The impact of preoperative breast MRI on the re-excision rate in invasive lobular carcinoma of the breast. Breast Cancer Res Treat. 2010;119(2):415–22.
87. De Bresser J, De Vos B, Van der Ent F, Hulsewe K. Breast MRI in clinically and mammographically occult breast cancer presenting with an axillary metastasis: a systematic review. Eur J Surg Oncol. 2010;36(2):114–9.
88. Lehman CD, Blume JD, Thickman D, et al. Added cancer yield of MRI in screening the contralateral breast of women recently diagnosed with breast cancer: results from the International Breast Magnetic Resonance Consortium (IBMC) trial. J Surg Oncol. 2005;92(1):9–15.
89. Lehman CD, Isaacs C, Schnall MD, et al. Cancer yield of mammography, MR, and US in high-risk women: prospective multi-institution breast cancer screening study 1. Radiology. 2007;244(2):381–8.
90. Lord S, Lei W, Craft P, et al. A systematic review of the effectiveness of magnetic resonance imaging (MRI) as an addition to mammography and ultrasound in screening young women at high risk of breast cancer. Eur J Cancer. 2007;43(13):1905–17.
91. Warner E, Plewes DB, Hill KA, et al. Surveillance of BRCA1 and BRCA2 mutation carriers with magnetic resonance imaging, ultrasound, mammography, and clinical breast examination. JAMA. 2004;292(11):1317–25.
92. McCormack VA, dos Santos Silva I. Breast density and parenchymal patterns as markers of breast cancer risk: a meta-analysis. Cancer Epidemiol Biomark Prev. 2006;15(6):1159–69.
93. Boyd NF, Guo H, Martin LJ, et al. Mammographic density and the risk and detection of breast cancer. N Engl J Med. 2007;356(3):227–36.
94. Berg WA, Zhang Z, Lehrer D, et al. Detection of breast cancer with addition of annual screening ultrasound or a single screening MRI to mammography in women with elevated breast cancer risk. JAMA. 2012;307(13):1394–404.
95. Sardanelli F, Giuseppetti GM, Panizza P, et al. Sensitivity of MRI versus mammography for detecting foci of multifocal, multicentric breast cancer in fatty and dense breasts using the whole-breast pathologic examination as a gold standard. Am J Roentgenol. 2004;183(4):1149–57.

96. Smith BD, Arthur DW, Buchholz TA, et al. Accelerated partial breast irradiation consensus statement from the American Society for Radiation Oncology (ASTRO). Int J Radiat Oncol Biol Phys. 2009;74(4):987–1001.

97. Dorn PL, Al-Hallaq HA, Haq F, et al. A prospective study of the utility of magnetic resonance imaging in determining candidacy for partial breast irradiation. Int J Radiat Oncol Biol Phys. 2013;85(3): 615–22.