Breast MRI

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Editors

Breast MRI
Diagnosis and Intervention

With 1040 Illustrations

With Forewords by Larry Norton, MD, and
Beryl McCormick, MD, Clifford Hudis, MD, and
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Springer

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To my parents, Jocelyn and James, who inspire me and made dreams come alive, and
To my husband, Giles Hunt, who makes life rich with laughter and love and supports me endlessly, and
To my daughter, Abigail, who makes it all worthwhile

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I dedicate this book to my husband, David Charles Perlman MD, my children, Daniel Joseph Perlman and Nina Beth Perlman, and my parents, Robert and Judith Liberman, for their love and support in this and all things.

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Foreword I

The book you are about to read is certainly important in itself, as it is an authoritative, practical, and scholarly guide to one of the most rapidly changing and increasingly valuable areas in breast medicine. But its true significance is best appreciated from the long-term historical perspective.

The advances in diagnostics and therapeutics that have transformed our modern world are the results of a revolution in biomedical philosophy that, while starting in the first centuries of the Common Era, is still in progress. This slow but inexorable ascendancy of the organ-based medical tradition of the Arabian-Persian-Hebrew schools and consequent decline of the ancient Greek reliance on manipulation of humors ("feed a cold; starve a fever") has brought functional anatomy into the very center of our thinking. Yet what began with vague concepts of gross organs and organ systems has now progressed into highly sophisticated cell biology, biochemistry, and genetics, even while structure-function linkage has been preserved as the rational core. We have learned to describe phenomena in increasing levels of detail, from the whole tissue down to the level of the single molecule. The process has spun off dramatic improvements in detection, prognostication, and intervention, and promises much, much more.

Seen in this context, the rise of magnetic resonance imaging of the breast is a vital contemporary example of an enduring historical development. The twentieth century saw both the emergence of breast surgery as the first treatment capable of curing some cases of breast cancer and its enhancement by radiation therapy and systemic drug administration. Breast imaging coevolved both to guide the therapeutic hand and to improve the diagnostic hand, thereby vastly augmenting the value of all three treatment modalities. But what we read in these pages is not just a chronicle of advances in the art of visualizing a mass. We are thrust into the middle of a sea change in our ability to assess—simultaneously and non-invasively or minimally invasively—the structure and function of the cells from which cancers arise and are sustained.

Hence, contemporary technology is beginning to provide what twenty centuries of medical progress has sought, a melding of anatomy, physiology, and therapeutics in real time and to strikingly beneficial effect. Fundamental concepts of the normal and cancerous breast are being challenged. Venerable terms like *preneoplastic stroma*, *preinvasive carcinoma*, *multifocality*, and *margin assessment* are being redefined. Our access to the earliest events in breast disease, the molecular events, is opened wider. Where all of this will lead is, of course, unknowable, but the direction is clear: clearer and deeper and more integrated understanding, all in the service of better management. That is the big picture, and that is what these pages really signify.

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Foreword II

Breast cancer is a major health problem for American women and it accounted for almost 40,000 deaths in 2003. Unlike many other forms of cancer, awareness among women of the risks associated with breast cancer is high and derives from many sources including health education programs promoting screening, extensive media coverage, and first-hand knowledge from friends or relatives with the diagnosis.

Despite this public awareness, our best screening tool, mammography, has a false-negative rate of 10% to 25%, depending on the series. Hundreds of women who participate in screening are falsely reassured that they are breast cancer free each year. Furthermore, mammography has limitations in its ability to accurately establish the extent of disease in the breast for some subsets of women undergoing treatment. For example, it may underestimate the extent of lobular carcinoma in up to 25% of cases. It is in this climate that interest has focused on MRI as an adjunct to mammography.

MRI has been a valuable imaging tool for many parts of the human anatomy since the early 1980s, but it was not widely used for imaging the breast until recently. Fewer than 5 years ago, the US Public Health Service Office on Women's Health organized a meeting to design and develop a research plan for optimization and clinical evaluation of breast MRI. At the time of the meeting, individual clinicians had research experience within a few specific areas of MRI, but the main conclusions of the meeting were that dissemination of breast MRI into the clinic had been slow, there was an urgent need for a lexicon similar to the BI-RADS™ system developed for reading mammograms, and breast MRI required dedicated breast equipment systems.

As detailed in this textbook, significant progress has been made in the development of MRI for the breast. MRI is now recognized as the most sensitive imaging modality for breast cancer, and it has been shown to provide clarity in many clinical situations in which dense breast tissue is not imaged well with routine mammography or with ultrasound. It has been particularly useful in demonstrating the extent of biopsy-proven cancers, especially invasive lobular cancers and ductal carcinoma in situ, which historically were not well imaged with conventional breast techniques. In such situations, the MRI may be useful in guiding both the surgeon and the patient regarding the appropriate choice of breast conservation versus mastectomy.

The sensitivity of MRI can be a challenge as well as a boon. In women with biopsy-proven cancer, MRIs obtained after wide local excision with pathologically close or involved margins may reveal enhancement that could represent a small volume of tumor that is not clinically relevant and has been sterilized in the past with breast radiation, or it could represent surgical artifact. Research in this area is ongoing and will be critical in broadening the utility of this modality.

The specificity of MRI-enhanced lesions in the breast is moderate. Until recently lesions imaged only on MRI and not on breast ultrasound or mammography were technically difficult to biopsy because ferromagnetic needles (MRI unsafe) could not be used in the localizing process if a magnet was required. Now, with several clinical systems commercially available using nonferromagnetic needles (MRI safe) instead of ferromagnetic devices to localize these lesions and sample tissue, better data will be generated. Also, breast imagers have learned a great deal regarding the timing and sequencing of the images.

At present, the clinical impact of breast MRI is uncertain. In a center with dedicated equipment and equally dedicated radiologists, it is probably useful for women with biopsy-proven breast cancers to exclude additional unsuspected disease. As noted previously, MRI can demonstrate the extent of disease in the breast, thereby assisting in decisions regarding appropriate primary surgery. For women who present with biopsy-proven breast cancer in an axillary node but for whom no primary lesion can be identified through physical examination or mammography, MRI can often direct the surgical team to an index lesion in the breast.

For patients with larger but technically resectable breast cancers who elect neoadjuvant chemotherapy in an effort to convert from mastectomy to breast conservation, MRI is an excellent tool to track the response of the index lesion to chemotherapy and determine if and when a limited surgical procedure is feasible.

In special situations, MRI may be useful for screening. For young women with strong family histories of breast cancer, or who carry a known genetic marker for this disease, mammography may be less useful because of their dense breast tissue. In this situation MRI may provide information that complements conventional screening.

As MRI technology improves and more is learned from clinical trials and retrospective studies, the application and utility of this modality should become clearer. It appears likely that MRI of the breast will play an increasingly important role in the diagnosis and management of selected patients with breast cancer.

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Preface

Breast magnetic resonance imaging (MRI) is creating a revolution in breast diagnosis and intervention. In the last decade, breast MRI has evolved from being an investigational technique to a clinically valuable tool for breast cancer detection and diagnosis. Individuals who perform or refer patients for breast imaging studies need to understand the indications for breast MRI, how to obtain and interpret the images, outcomes of breast MRI in specific scenarios, and how to perform biopsy of lesions detected by MRI only. This book was created to fill that need.

This book is organized into two Parts. Part I, the text, starts with the basics, including a historical overview, technique, how to set up a breast MRI program, the normal breast, the axilla, the breast MRI lexicon, and kinetic analysis. MRI features of benign lesions, ductal carcinoma in situ (DCIS), and invasive breast cancer are discussed in detail. Uses of breast MRI are presented, including high-risk screening, breast cancer staging, assessment of residual disease, MRI after breast cancer treatment, evaluation of silicone breast implants, and other clinical scenarios. The emerging technology of breast MRI spectroscopy is discussed. Specific chapters address MRI-guided interventional procedures, including step-by-step instructions on how to perform MRI-guided needle localization and MRI-guided vacuum-assisted biopsy, and suggestions for challenging cases. The final chapter discusses the potential for breast MRI in percutaneous ablation of breast cancer in the future.

Part II is an atlas of breast MRI. Case examples illustrate the normal breast as well as malignant lesions (distribution of tumor, staging, metastasis, invasive cancer and also have a strong family history of breast cancer and in women who have specific histologies (e.g., invasive lobular) in the index cancer. When breast MRI is used, it should supplement, but not replace, mammography.

For radiologists embarking on a breast MRI program, it may be helpful to start with women who have proven breast cancer, to look for additional ipsilateral and contralateral disease. An essential component of any breast MRI program is the ability to perform localization and biopsy of lesions identified only by MRI. It is invaluable to include mammography technologists experienced at stereotactic biopsy in MRI-guided interventional procedures. Physicians who perform breast MRI should track the results at their own institutions and share this information with their referring clinicians, so that patients can be appropriately counseled. A negative breast MRI does not spare the need for biopsy of a lesion that is suspicious based on mammography or physical examination. It should be remembered that breast MRI is expensive, that some women (e.g., those with claustrophobia, pacemakers, or aneurysm clips) may not be candidates for breast MRI, that there is variability in technique, interpretation, and insurance reimbursement, and that no studies have shown breast MRI to save lives.

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I
Principles and Practice

1
Breast Magnetic Resonance Imaging: Historical Overview

Joo Young Melissa Lee and Elizabeth A. Morris

Contrast-enhanced magnetic resonance imaging (MRI) of the breast was first performed in the late 1980s in women with biopsy of proven carcinomas. Heywang and colleagues[1] demonstrated that breast carcinomas showed significant enhancement following the administration of contrast material. Most tumors demonstrated contrast enhancement within the first 5 min. However, further investigations showed that not only do malignant lesions enhance, but benign lesions can also show a similar degree of enhancement. Thresholds for significant enhancement were used with normalized units of enhancement to attempt to differentiate more reliably between the different tissues; however, overlap existed.[2] Therefore, multiple differing attempts were made at developing more defining characteristics to distinguish benign from malignant processes.

1. Dynamic Approach

The earliest MRI studies of the breast were performed with a T1-weighted spin echo sequence before and after intravenous gadopentate dimeglumine (Gd-DTPA) with an imaging time of at least 5 min and a slice thickness of 5 mm. With the development of fast T1-weighted gradient echo pulse sequences, imaging of the breast in thinner contiguous sections along with dynamic MRI of the whole breast became feasible. With this new technique, it became possible to repeat the same image at short time intervals and therefore characterize a lesion's enhancement over a shorter interval of time. Using these data, a signal intensity curve can be generated and, thereby, the curve's rate and velocity can be analyzed.

Studies with faster imaging techniques demonstrated that the initial phase of rapid contrast uptake during the first 2 to 3 min contained valuable information to distinguish between benign and malignant tissue. Subsequently, a flurry of studies was performed using these new techniques. Using a two-dimensional (2D) gradient echo sequence, Kaiser and colleagues[3] found that malignancies showed a sudden increase in signal intensity of 100% within the first 2 min. Gradual, mild contrast uptake was seen in benign tissue. Fibroadenomas showed intense enhancement but at a much slower rate than carcinomas. A series performed by Stack and coworkers[4] had similar findings, with malignant lesions showing a steep increase during the first 60s, followed by a smaller, more gradual increase over 4 to 8 min. Benign tissue only showed a gradual increase in signal intensity at a slower rate, while fibroadenomas demonstrated a marked increase in signal intensity over an 8-min period. Several different attempts were made by other investigators by varying the imaging parameters and changing the enhancement criteria to improve specificity. Boetes and colleagues[5] used a turboFLASH subtraction technique and classified lesions as suspicious if they enhanced within 11.5s after the aorta opacified. Gilles and coworkers[6] used a T1-weighted spin echo sequence with subtraction imaging and obtained an acquisition time of 47s. They classified any enhancement concomitant with early normal vascular enhancement as a positive finding for malignancy, obtaining a sensitivity of 95% and specificity of 53%. However, the validity of all these criteria was questioned by later investigators, who found even higher signal intensities in benign lesions such as fibroadenomas.[7,8] These investigators found that while cancers tend to enhance faster than benign lesions, there is still a clear overlap in enhancement rates of benign and malignant lesions.

2. Time Intensity Curves

In a more recent study, Kuhl and colleagues[9] analyzed not only the enhancement pattern of a lesion in its early phase, but also in the intermediate and late phases. By using a 2D

dynamic technique, they qualitatively analyzed the shape of the time-signal intensity curve of suspicious lesions over time and described three different curves: type I (steady) curve corresponds to a straight or slightly curved enhancement pattern with the enhancement progressively increasing over time; type II (plateau) curve levels off after the initial sharp level of enhancement; and a type III (washout) curve has a drop in signal intensity after the initial upstroke, indicating washout of contrast. These curves were generated on only focal mass-like lesions that appeared morphologically suspicious and showed a signal intensity increase of more than 60% on the first postcontrast images. A region of interest was placed in the area of the most rapid and strongest enhancement and was quantified by the change in signal intensity before and after the injection of Gd-DTPA. A type I curve was rated indicative of a benign lesion, type II was suggestive of malignancy, and type III was indicative of a malignant lesion. Using these curves, they achieved a sensitivity of 91% and specificity of 83%.

Although this technique appears promising, limitations exist that must be taken into consideration. First, only those lesions that showed suspicious enhancement or suspicious morphology characterized as ill-defined or irregular contoured borders were included in the study, thus limiting lesions such as ductal carcinoma in situ, which may not demonstrate rapid enhancement or present as a mass-like lesion. In addition, studies have also shown that carcinomas can present as small focal masses with visually well-defined margins[10] or present as rim-enhancing masses,[7] lesions that would not have been included in Kuhl's study.

False-positive results are associated with the exclusive use of the dynamic technique, particularly with fibroadenomas and lymph nodes. Although some studies have shown less intense enhancement with fibroadenomas,[3,4] other studies have shown early intense enhancement.[7,11] This possible disparity between studies may be explained by the histologic variability of fibroadenomas. In Orel's series, she notes she had "young" fibroadenomas that exhibited marked, rapid enhancement. This variability of enhancement of fibroadenomas may be related to degree of fibrosis of the tumor as depicted in a study by Brinck and coworkers[12] He showed that the amount of fibrosis within a fibroadenoma correlates with the degree of enhancement following intravenous Gd-DTPA. Fibroadenomas with increased fibrosis on histopathology have less intense enhancement following intravenous contrast, which may account for the variability between studies.

Another potential false-positive result is intramammary lymph nodes. Intramammary lymph nodes with lymphoid hyperplasia have also proven to demonstrate rapid enhancement following contrast administration, thus mimicking carcinoma. Gallardo and colleagues[13] presented three cases of enlarging breast masses seen on MRI that showed strong and rapid uptake, raising the suspicion for malignancy and, therefore, biopsy was performed. Pathology ultimately yielded a diagnosis of lymphoid hyperplasia.

3. Morphologic Approach

The dynamic approach to differentiating benign and malignant lesions has not been fully corroborated by other studies. Some investigators have found no significant difference in the enhancement characteristics between benign and malignant lesions.[7,8,10] In a study of 74 lesions, Harms and colleagues[11] showed significant overlap between malignant and benign lesions such as fibroadenomas, sclerosing adenosis, and proliferative fibrocystic change, obtaining a sensitivity of 94% and specificity of 37%. In this study, Harms and colleagues suggest that analyzing a lesion's morphologic characteristic may help to improve the specificity of MRI. Similar to its use in mammography and ultrasound, border characteristics such as well defined or spiculated may be a useful adjunct to enhancement features.

Subsequently, Orel and coworkers[7] evaluated both the morphologic and enhancement characteristics of suspicious breast lesions. They used a fat-saturated spoiled gradient echo sequence to acquire high-resolution images along with temporal information. Their data confirmed some of the previous studies that signal intensities and enhancement characteristics overlapped between benign and malignant lesions, particularly fibroadenomas. Although carcinomas had a tendency toward more rapid enhancement and washout, there was still a significant overlap with enhancement patterns of fibroadenomas. In her morphologic analysis of lesions, Orel discovered architectural features were helpful in differentiating between benign and malignant lesions. Carcinomas exhibited irregular borders and rim enhancement, while fibroadenomas often had lobulated borders, with nonenhancing internal septations. In a study of 192 patients, Nunes and colleagues[14] exclusively analyzed architectural features to develop a tree-shaped interpretation model to distinguish benign from malignant lesions. Masses with irregular borders and rim enhancement were associated with carcinoma, while masses with lobulated borders and internal septations were associated with fibroadenomas. Nonmass enhancement was also described, which included ductal and regional enhancement. Ductal enhancement correlated with ductal carcinoma in situ, while regional enhancement was not particularly predictive of either benign or malignant disease.

4. Combination of Dynamic and Morphologic Approaches

Currently, it is realized that both dynamic and morphologic data can be helpful in the assessment of breast MRI lesions. In an attempt to optimally use both morphologic and temporal features, Kinkel and colleagues[15] used a three-dimenional (3D) sagittal fat-suppressed T1-weighted fast gradient-recalled echo sequence to obtain high spatial resolution MRIs. Semidynamic information was acquired by obtaining three sets of images at three time-points following the administration of intravenous contrast. The signal intensity on the first postcontrast image acquired at 2 min and 30 s was then compared with the second set of images acquired at 7 min and 30 s. Enhancement kinetics were analyzed visually without the use of a region of interest. *Washout* was defined as any visual decline in signal intensity from the first set of images to the second. *Plateau* enhancement was defined as stabilization in signal intensity, and *progressive* enhancement was defined as an increase in signal intensity between the two sets of images. The morphologic parameters included lesion type (mass vs. nonmass), mass margin, internal enhancement, and T1- and T2-weighted unenhanced visibility. The combination of evaluating the margin (smooth vs. irregular or spiculated) and washout pattern of a lesion resulted in a sensitivity and positive predictive value of 97% and specificity and negative predictive value of 96%. The limitation of this study was that the lesions evaluated were known palpable masses or suspicious findings seen on mammography; therefore, nonmass enhancement, which can often be seen with ductal carcinoma in situ, was not fully evaluated.

In a more recent study by Liberman and coworkers,[16] only lesions exclusively detected on MRI were analyzed by using the three time-point technique with T1-weighted 3D fat-suppressed fast spoiled gradient echo sequence. Morphology of the lesions and visual assessment of the enhancement kinetics were analyzed. For mass lesions, features that correlated with carcinoma were spiculated margin, rim enhancement, and irregular shape. For nonmass lesions, segmental, clumped, linear, and ductal enhancement was predictive of malignancy. The visually assessed kinetic patterns were not significant predictors of carcinoma, but it was noted that washout was more likely in the presence of invasive carcinomas versus ductal carcinoma in situ.

5. Conclusion

Two different concepts have evolved to try to improve the specificity of MRI. One focuses on high spatial resolution to analyze a lesion's morphologic characteristic, and the other focuses on temporal resolution to analyze a lesion's enhancement pattern. With the technology previously available, both of these features cannot be simultaneously optimally analyzed.[17] When a dynamic technique is used, spatial resolution will be sacrificed, thus compromising its sensitivity for small and multifocal breast carcinomas. Efforts to develop a technique that combines both rapid acquisition with preservation of high spatial resolution and complete integration of both kinetic and morphologic features have succeeded. Newer techniques (parallel imaging) use multiple MRI received coil elements to encode spatial information in addition to traditional gradient encoding. By reducing gradient encodings, shorter scan times can be achieved. Parallel imaging is beginning to be used in the breast with excellent results and has allowed optimization of both spatial and temporal resolution so that all features of breast lesions can be optimally assessed.

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2
Breast Magnetic Resonance Imaging Techniques

Nola M. Hylton

Magnetic resonance imaging (MRI) of the breast is finding wider clinical application as an adjunct diagnostic procedure to mammography and ultrasound. Because of its high sensitivity and effectiveness in dense breast tissue, MRI can be a valuable addition to the diagnostic work up of a patient with a breast abnormality or biopsy-proven cancer. The major limitation of breast MRI is the low-to-moderate specificity, which in combination with high sensitivity can lead to unnecessary biopsy, patient anxiety, and cost. Nonetheless, there are consistent findings emerging that show contrast-enhanced MRI to be effective for early detection of cancer in high-risk women, and superior to mammography for identifying and demonstrating the extent of diffuse and multifocal breast cancer.[1–4]

There are a number of clinical indications for which breast MRI is believed to add value to the conventional clinical and diagnostic work up, including (1) evaluation of patients with axillary carcinoma and negative mammographic and clinical findings, (2) evaluation of women with questionable mammographic findings and previous breast surgery to distinguish postsurgical scar from recurrent carcinoma, and (3) staging of the extent of a cancer diagnosed by percutaneous needle biopsy. Other indications are less well accepted and are being evaluated largely in the research setting. The sensitivity of MRI to breast carcinoma, particularly in dense breast tissue, has led to the emerging role of MRI in breast cancer screening for women identified to be at high risk. Early results from a number of trials in the United States, Canada, the Netherlands, and Europe show between 2% and 4% cancer yield on screening MRI in the high-risk population.[5–7] Many of the cancers discovered by MRI were occult on mammography and clinical examination. A number of important questions remain to be answered before MRI can be recommended for screening of high-risk women, including the appropriate risk level at which screening should be recommended, and the appropriate screening interval.

The high staging accuracy of breast MRI has led to its use for assessing tumor response to neoadjuvant chemotherapy. Magnetic resonance imaging can contribute in several ways to the management of patients receiving preoperative chemotherapy, including the determination of initial extent of disease for proper staging, early identification of poor responders, and identification of the presence and extent of residual disease for surgical planning. Magnetic resonance imaging measurements of tumor response may have predictive value for disease recurrence and responsiveness to novel therapeutics.[8–10] This potential is being explored in a number of clinical trial venues.

The various clinical indications for breast MRI can place different requirements on how the examination is performed. Clearly, a bilateral examination must be used if screening is the purpose, while unilateral imaging may be appropriate for some diagnostic indications to maximize spatial resolution for better morphologic assessment. In addition to these types of considerations, the emphasis of temporal and spatial resolution, fat suppression, and other factors may be influenced by radiologist preference.

The major challenge for breast MRI is the need to improve the specificity of the technique to avoid the unnecessary procedures and patient anxiety that follow a false-positive finding. This may come about through better integrated biopsy methods, new contrast agents with greater specificity, and/or computer-aided methods to aid radiologic interpretation.

1. MRI Versus Mammography

Mammography has an established role in breast cancer screening and diagnosis. Mammography is an X-ray method that has been optimized for evaluation of breast tissue and the detection of breast cancers, while minimizing radiation dosage. The MRI signal is based on different physical principles than mammography and reflects the

density of water protons in tissue and their magnetic interactions with molecules in their local environment. The MRI signal is strongly influenced by these magnetic interactions, which affect how quickly the water protons can return to equilibrium (a process characterized by the T1 and T2 relaxation times) after receiving radiofrequency (RF) energy from an external source (the RF coil). Parameters of the MRI technique can be adjusted to change the weighting of the T1 and T2 relaxation times, thus allowing image contrast to be manipulated. The MRI signal can also be sensitized to physiologic conditions, such as local water diffusion, blood flow, blood oxygenation, and pH levels. In the application to breast imaging, MRI is performed using a T1-weighted technique that is sensitive to the accumulation of gadolinium-based contrast agents, which act to shorten T1 and increase signal intensity. Thus, an early (within 2 min) and significant signal increase in an area of breast tissue indicates a greater density and/or higher leakiness of microvessels, which can be a reflection of tumor angiogenesis. While most breast malignancies show such a signal enhancement, not all signal enhancements represent cancer, leading to the high sensitivity, but low-to-moderate specificity of breast MRI.

The different physical properties of mammography and magnetic resonance imaging support their complementary role in breast imaging (Table 2.1). With mammography, X-rays are projected through the thickness of the breast in two orthogonal directions (cranial-caudal and lateral-medial oblique) to minimize the problem of overlapping structures. Mammography is relatively quick to perform and inexpensive. Decades of experience with large-scale breast cancer screening programs and the more recent federal implementation of mammographic quality standards have led to optimized performance of mammography equipment and radiologic interpretations in high-volume centers.

Two attractive features of MRI for application to breast imaging are its three-dimensional format and strong soft-tissue contrast. These features allow the anatomical structure of the breast to be viewed in great detail. The anatomic detail alone, however, is not sufficient for making a diagnostic assessment. Malignant lesions are often indistinguishable from normal and benign structures on T1-weighted or T2-weighted imaging. Cancer detection is aided by the use of a contrast agent, as described earlier. The increased density and leakiness of microvessels associated with cancer growth can be detected by an early, significant increase in the signal intensity after contrast is injected.

Contrast-enhanced MRI is not, however, sensitive to microcalcifications, which can be an early indication of breast disease and is a frequent finding on mammography. While calcium deposits can occasionally be seen on MRI as tiny signal voids, breast MRI is not a reliable method for detecting microcalcifications. Signal intensity changes with contrast injection are an indication of an altered microvasculature, a separate and distinct manifestation of breast disease than microcalcifications. Conventional mammography is not a sensitive indicator of increased microvasculature associated with tumor neo-angiogenesis. This again supports the complementary role of mammography and breast MRI.

Table 2.1. Complementary Features of Mammography and MRI

Feature	Mammography	MRI
Signal basis	X-ray	Water proton NMR
Format	2D projection	3D multislice
Breast compression required	Yes	No[a]
Contrast injection required	No	Yes
Examination time	Short (5–10 min)	Long (30–45 min)
Demonstrates calcifications	Yes	No
Effective in dense breast tissue	No	Yes

[a] Mild compression can be used to stabilize breast.
Abbreviations: 2D, two-dimensional; 3D, three-dimensional; NMR, nuclear magnetic resonance.

2. Technical Requirements for Performing Breast MRI

Magnetic resonance imaging is by nature a very multiparametric technique involving trade-offs between image characteristics such as contrast, signal-to-noise ratio, resolution, field–of view, and scan time. Other parameters can also be varied, including orientation (transaxial, sagittal, or coronal), format (unilateral or bilateral), and use of fat suppression. Each of these variables has implications for the ability of MRI to detect and characterize small lesions in the breast. Because of the high degree of flexibility in choosing the imaging parameters, there is a great deal of variation in imaging techniques described in the literature, making it difficult to compare results and determine the true performance of breast MRI.

Two important technical requirements for breast MRI are the use of a dedicated breast coil and administration of a contrast agent when looking for breast cancer. A contrast agent is not required to look for implant rupture or leakage. For implant evaluation, T2-weighted fast spin echo techniques using inversion recovery for fat suppression and chemical saturation of the water signal can produce images of silicone only. However, noncontrast methods are not effective for detecting breast malignancies.

3. Imaging Coils

State-of-the-art breast coils typically consist of multicoil arrays with a geometric design that provides a high signal-to-noise ratio over an area covering both breasts, with extension beyond the chest wall and into the axilla in the majority of patients. Other considerations in the design of breast coils include patient comfort and open access to the breast for performing MRI-guided wire localizations and needle biopsies. While general surface coils can produce high-quality breast images, they are likely to suffer more from poor homogeneity and inconsistent image quality than a dedicated breast coil. Patient comfort is a significant issue in the design of breast coils because of the need to image in the prone position with the upper torso elevated. The space constraint often results in discomfort to the patient's neck and shoulders.

4. Patient Preparation and positioning

As clinical usage of breast MRI increases, consistency of performance becomes more important. In addition to using a dedicated breast coil, attention to patient positioning can contribute to better examination performance. Because of the relatively long duration that patients are required to remain still, generally without sedation, it is advisable to make patients as comfortable as possible before the start of the examination. Breast MRI examinations are performed with patients lying in the prone position, with both breasts hanging freely in the bilateral openings of the breast coil support. Prone positioning helps to minimize the effects of respiratory motion, although the pendant shape of the breast in this position differs from the compressed shape when the patient is upright during mammography or the flattened shape when the patient is supine during surgical procedures. Depending on the individual, patients may find it more comfortable to keep both arms above their head, by their sides, or one in each position. Placement of an intravenous catheter for contrast agent or access to an injection site in the arm or on the hand for manual injection may require that at least one arm be positioned above the head. Following adjustments of position for patient comfort, the position of the breast should be checked again to ensure that each breast is hanging as completely and deeply as possible within the respective coil opening with the nipple pointing straight down. Distortions of the breast or only partial placement of the breast in the coil well can result in signal hotspots, poor image quality in the regions of the chest wall and axilla, and anatomical distortions that make image interpretation difficult. Inconsistent positioning on sequential examinations of the same patient can make it difficult to compare findings.

Breast MRI that is performed to evaluate a patient for breast cancer requires the use of a contrast agent. Noncontrast MRI is not sensitive to the presence of breast carcinoma and is not considered to be diagnostic. Breast MRI is most commonly performed using one of the gadolinium-based low-molecular-weight MRI contrast agents that are currently approved for human use. Gadolinium is a T1-shortening agent and the accumulation of gadolinium in tissue following intravenous injection reflects alterations in vascular density or permeability that can indicate cancer. The majority of studies reported in the literature use either a single dose (0.1 mmol/kg body weight) or double dose (0.2 mmol/kg body weight) of contrast agent. Both dose levels have demonstrated efficacy with little strong data to support one dose over the other. Because the cost of contrast agent is not insignificant, a single dose is most often recommended. Contrast is usually administered via an indwelling catheter as either a bolus injection or infusion. The mode of injection has implications for pharmacokinetic modeling of the signal intensity changes, but either method can be used. Consistency of the contrast injection method is most important and use of a power injector is recommended, when possible.

5. Image Acquisition Methods

As with all MRI applications, image quality will be affected by the choice of acquisition parameters, including the field-of-view and image matrix (which determine resolution), the timing parameters, and the number of signal averages. For dynamic contrast-enhanced techniques, relatively short scan times are needed to sample the time course of signal enhancement after contrast is injected. For breast cancers the peak enhancement occurs within approximately the first 2 min after bolus injection. Thus, to adequately sample the washin and washout of contrast, image acquisition needs to be repeated at 1 min or shorter intervals for the first several minutes when signal intensity change is most rapid. The time course of the signal intensity can be analyzed using a two-compartmental model of the exchange of contrast agent between the intravascular and extravascular/extracellular space. With knowledge of the arterial input function (AIF; signal change measured in a nearby large artery) and the initial tissue T1 value, the two pharmacokinetic constants, the exchange constant k_{trans} and the fractional blood volume fBV, can be solved. These constants have physiologic relevance to the angiogenic phenotype of cancer and have been shown to be predictive of tumor grade, metastatic potential, and response to treatment.[11–16] Less rigorous methods that do not require the measurement of AIF or T1 can be made with certain assumptions and approximations. Other methods for analyzing the signal intensity time curves are based on

empirical measurements of quantities such as area under the curve (AUC), initial slope of enhancement, or signal enhancement ratio (SER).[11,17,18]

While some studies suggest that very short scan times are required (on the order of 2–10s) in order for accurate modeling of the pharmacokinetics of contrast uptake,[19] this recommendation does not take into account the averaging of heterogeneous tissue that can result from the accompanying reduction in spatial resolution, volume of coverage, and/or signal-to-noise ratio.

Many advocate that rather than compromise image quality for dynamic scanning, longer scan times be used to improve the resolution and signal-to-noise ratio and to use fat suppression. Scan time requirements can then be relaxed to acquire only 1 to 2 postcontrast images, with the first postcontrast image timed to coincide with the expected peak of enhancement at about 2 min. (This is accomplished using a k-space trajectory for which the lower order phase encoding lines are acquired near the 2-min time point.) Three-dimensional, fat-suppressed, fast gradient echo imaging is usually used in this case to acquire high spatial resolution breast magnetic resonance images. Assessment of the degree of enhancement and lesion morphology is used to make the diagnostic interpretation.

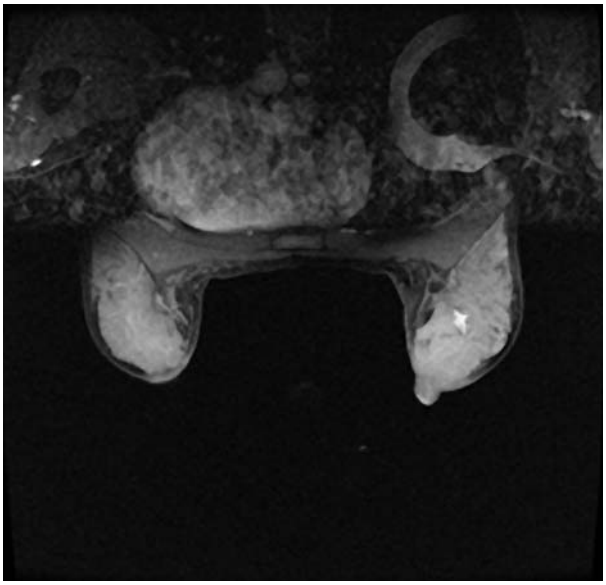

FIGURE 2.1. Bilateral MRI acquired in axial orientation shows a brightly enhancing mass corresponding to a fibroadenoma in the left breast of a patient with very dense breast tissue. Note aliasing of signal from the arms and image blurring due to motion artifact seen posterior to chest wall. Assignment of the phase encoding direction to the left-right direction minimizes artifact-related image degradation in the breast tissue. (Reproduced with permission from American College of Radiology (ACR). ACR BI-RADS®–Magnetic Resonance Imaging. In: *ACR Breast Imaging Reporting and Data System, Breast Imaging Atlas.* Reston, VA. American College of Radiology; 2003.)

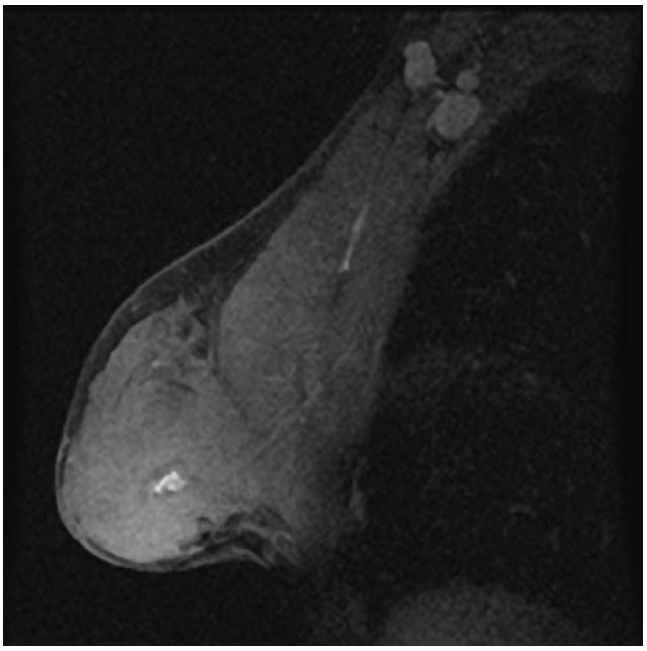

FIGURE 2.2. Unilateral sagittal image through the lesion shown in the left breast of the bilateral image in Figure 2.1. The higher spatial resolution demonstrates the well-circumscribed nature of the lesion and the internal dark septations that are characteristic of fibroadenomas. (Reproduced with permission from American College of Radiology (ACR). ACR BI-RADS®–Magnetic Resonance Imaging. In: *ACR Breast Imaging Reporting and Data System, Breast Imaging Atlas.* Reston, VA. American College of Radiology; 2003.)

Numerous studies have been published regarding the diagnostic usefulness of morphologic features, showing the presence of rim-enhancement, spiculated margins, and linear or ductal shapes, to be indicative of malignancy. Other features, including smooth margins and the presence of dark internal septations, are associated with benign disease. The ACR BI-RADS™ reporting system for breast MRI has recently been published and illustrates many of the morphologic findings encountered on contrast-enhanced breast MRI.

Figures 2.1 through 2.3 illustrate some of the tradeoffs that accompany the choice of imaging parameters. The bilateral axial magnetic resonance image in Figure 2.1 was acquired as part of a screening examination and demonstrates an enhancing mass in the left breast of a woman with very dense breast tissue. There were no significant findings in the right breast. In cases of diffuse or regional enhancement, symmetry or asymmetry with the contralateral breast can be helpful in deciding the significance of the finding. Figure 2.2 shows a sagittal section through the same lesion as in Figure 2.1, taken from a unilateral breast examination of the same patient performed 1 wk after the screening examination. The well-circumscribed margin of the lesion

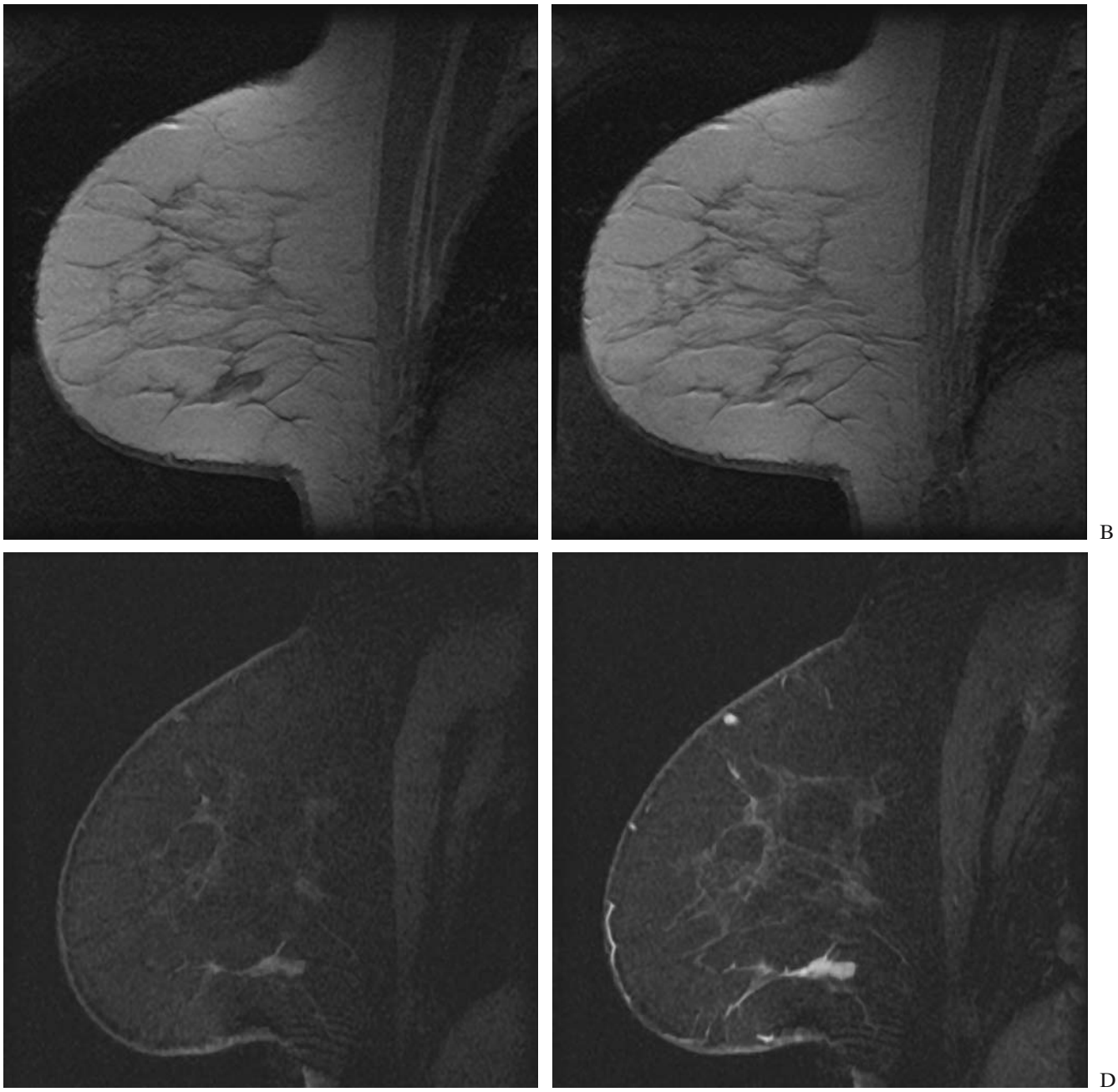

FIGURE 2.3. Pre-(left) and post-(right) contrast images from dynamic two-dimensional (A) and high-resolution three-dimensional (C) examinations of the same patient using pulse sequence parameters similar to those listed in Table 2.2. The post-contrast dynamic image (B) corresponds to the 30-s postcontrast time point. The enhancing mass in the lower central breast showed rapid contrast enhancement and washout on the dynamic series, and was found to be an invasive ductal carcinoma. The irregular lesion shape, presence of spicules, and heterogenous internal enhancement pattern are better appreciated on the high-resolution section (D). (Reproduced with permission from American College of Radiology (ACR). ACR BI-RADS®–Magnetic Resonance Imaging. In: *ACR Breast Imaging Reporting and Data System, Breast Imaging Atlas.* Reston, VA. American College of Radiology; 2003.)

and presence of dark internal septations are better demonstrated on the high resolution image and are characteristic of the confirmed diagnosis of fibroadenoma. In Figure 2.3, pre- and postcontrast images from dynamic and high-resolution studies in the same patient are compared. Rapid enhancement and washout was measured in the lesion on the dynamic series, while the spiculated margins of the lesion are better appreciated on the high spatial

Table 2.2. Example Pulse Sequences for Dynamic and High-Resolution Breast MRI

	Dynamic	High Resolution
Acquisition type	2D	3D
Pulse sequence type	Spin echo	Gradient echo
TR	⩽100 ms	⩽20 ms
TE	4.5 ms	4.5 ms
Flip angle	90°	⩽45°
Field of view		
Unilateral	16–22 cm	16–22 cm
Bilateral	32–40 cm	32–40 cm
Matrix size	128 × 128	256 × 192
Slice thickness	3–5 mm	1–2 mm
Number of slices	5–10	32–128
Fat suppression	Subtraction	Chemical saturation or selective water excitation
Scan time	⩽1 min	2–4 min

General guidelines for all examinations: use breast RF coil, avoid anterior/posterior phase direction, avoid strong compression.
Abbreviations: 2D, two-dimensional; 3D, three-dimensional; TE, echo time; TR, repetition time.

resolution image. Both findings are highly suggestive of malignancy.

The relative diagnostic usefulness of the pharmacokinetic parameters acquired at moderate spatial resolution versus morphologic feature assessment using volumetric imaging and maximized spatial resolution is difficult to establish and is still being debated. As breast MRI technology advances, these two strategies are converging. Improved techniques that combine both kinetic and morphologic information will also be aided by the availability of longer circulating contrast agents that are under development. Examples of pulse sequence specifications for dynamic and high-resolution techniques are listed in Table 2.2. More recent advances in MRI technology should also contribute to improved breast imaging. Parallel imaging has become available on a number of commercial scanners and allows the simultaneous acquisition of two separate volumes centered on the left and right breasts. This effectively enables bilateral, high-resolution imaging. Novel k-space sampling strategies using spiral or radial trajectories can also lead to gains in efficiency and better immunity to motion. Hybrid techniques are also being introduced that acquire interleaved k-space trajectories that can be separately reconstructed to produce high temporal resolution/low spatial resolution images for dynamic analysis, or can be combined and reconstructed to produce low temporal resolution/high spatial resolution images.[20] Thus, the same data set can be used optimally for both kinetic and morphologic analysis.

6. Fat Suppression

Active fat suppression can improve the detectability of small enhancing lesions, but generally adds to the total scan time. Fat suppression is generally performed by taking advantage of the spectral separation between the fat and water resonances. With chemical saturation techniques, a spectrally selective RF pulse is used to suppress the fat peak prior to issuing the normal excitation RF pulse. Fat therefore does not contribute to the subsequent signal measurement. The fat suppression pulse effectively lengthens the TR, and thus the total scan time. Conversely, water-only excitation pulses can be used, such as is used in the RODEO technique.[21] Other methods, such as periodic inversion pulses, are used to achieve fat suppression with reduced time penalty. Because the spectral separation between fat and water increases with field strength, spectral saturation fat-suppression techniques work more effectively at higher field strengths. In general, these techniques require field strengths of 1 Tesla or higher.

Image subtraction can be used to achieve the effect of fat suppression, but caution should be used in interpreting subtracted images. Subtracted images should be interpreted in conjunction with original unsubtracted images. Image subtraction removes all nonenhancing tissue and, thus, normal and nonenhancing tissue structures are no longer apparent in the subtracted image. For example, enhancement surrounding a biopsy cavity might appear as a rim-like enhancement with a centrally nonenhancing center. Image subtraction cannot be used if significant patient movement occurs between pre- and postcontrast images. Slight patient motion may not be easily detected, but can result in bright and dark edges that correspond to the misregistration between pre- and postcontrast images. Care should be taken to assure that small bright structures are not the result of slight misregistration.

7. Image Postprocessing

One breast MRI examination can generate hundreds of images. A complete diagnostic review has to consider both the spatial relationship of features on multiple slices as well as how those features change over time with the passage of contrast. Postprocessing is used to reduce the number of images for review. Subtraction is one level of postprocessing that can be used to highlight the enhancing features in the image. As mentioned earlier, subtraction is commonly used as a passive method of fat suppression. Another useful postprocessing tool is the maximum intensity projection (MIP), a ray tracing method that projects the brightest pixel value along each parallel ray projected through the volume of data, onto a two-dimensional surface. Maximum intensity projection images can be created from multiple angles and displayed sequentially in a cine loop to give a three-dimensional representation of the image volume. The MIP is most often used with magnetic resonance angiography to create projection images of vascular structures such as the carotid arteries. However, the MIP is also effective for contrast-enhanced,

fat-suppressed images of the breast because the brightest structures are likely to be vessels and enhancing tissue. The contrast on MIP images can be enhanced if image subtraction is performed prior to creating the MIP image. Maximum intensity projection images are very effective for demonstrating the distribution of disease in the breast in relation to the skin, nipple, chest wall, and large vessels. The MIP is not reliable for evaluating the internal pattern of lesions or possible extension of disease to the chest wall or skin. These assessments should be made from the individual slice images. There are numerous commercial software packages available for visualization and display of medical images and most offer capabilities to perform volume rendering, cut-away views, and color-coded displays, in addition to MIP rendering.

Quantitative information can be extracted from MRIs by making measurements in user-defined regions of interest (ROIs), or by creating parametric maps in which an

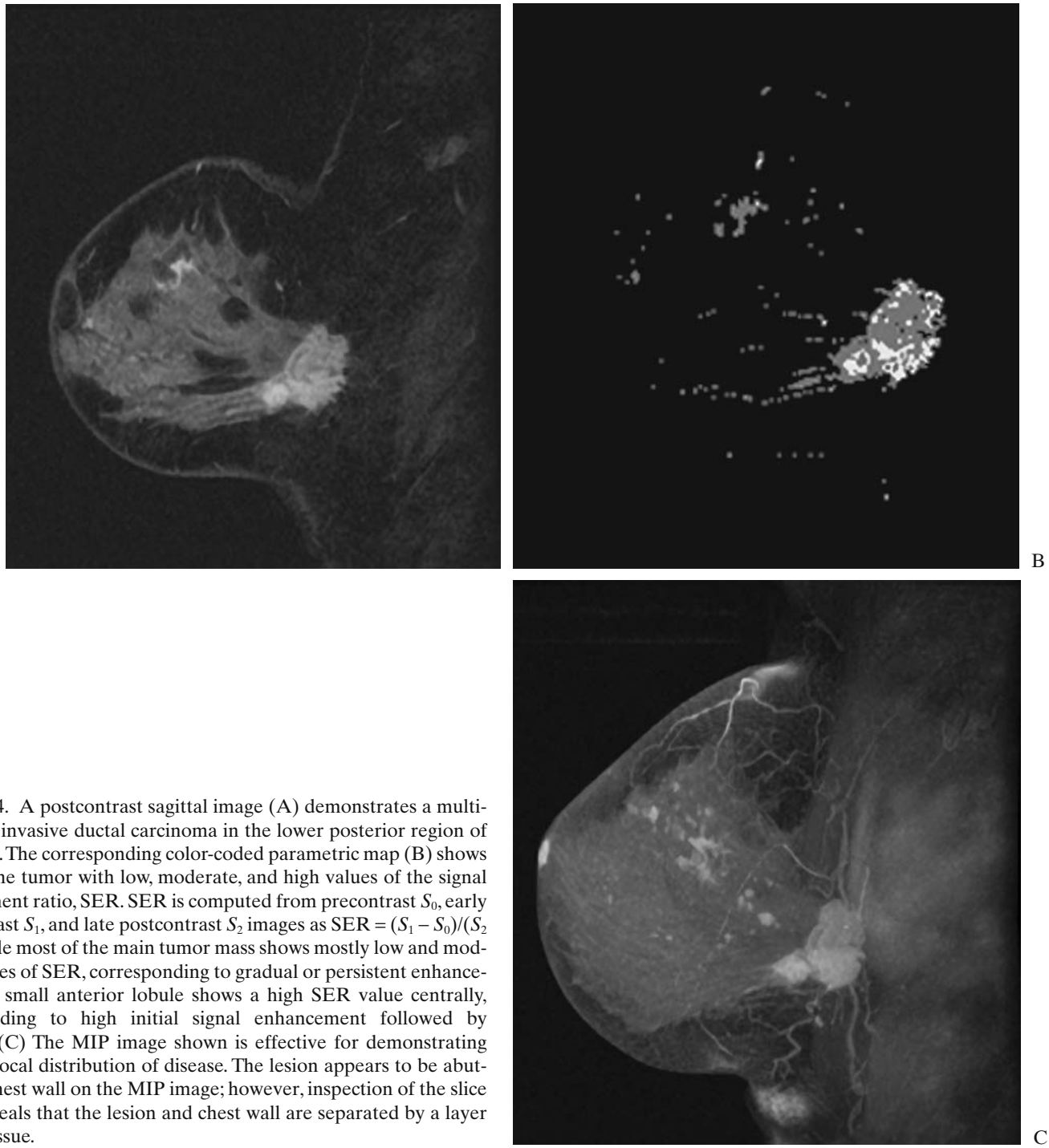

FIGURE 2.4. A postcontrast sagittal image (A) demonstrates a multilobulated invasive ductal carcinoma in the lower posterior region of the breast. The corresponding color-coded parametric map (B) shows areas of the tumor with low, moderate, and high values of the signal enhancement ratio, SER. SER is computed from precontrast S_0, early postcontrast S_1, and late postcontrast S_2 images as SER = $(S_1 - S_0)/(S_2 - S_0)$. While most of the main tumor mass shows mostly low and moderate values of SER, corresponding to gradual or persistent enhancement, the small anterior lobule shows a high SER value centrally, corresponding to high initial signal enhancement followed by washout. (C) The MIP image shown is effective for demonstrating the multifocal distribution of disease. The lesion appears to be abutting the chest wall on the MIP image; however, inspection of the slice image reveals that the lesion and chest wall are separated by a layer of fatty tissue.

image is created from the calculated value of the parameter of interest at every pixel. For example, values of k_{trans}, derived from the signal intensities over a time series of images collected before and after contrast injection can be mapped to a color scale with blue denoting low values of k_{trans} and higher values moving increasingly toward red.

Figure 2.4(A) shows one section through a lobulated mass in the lower, posterior region of the breast, corresponding to an invasive ductal carcinoma. The corresponding parametric map in Figure 2.4(B) shows low (dark gray), moderate (medium gray), and high (white) values of the signal enhancement ratio (SER) parameter. Signal enhancement ratio is computed from precontrast S_0, early postcontrast S_1, and late postcontrast S_2 images as SER = $(S_1 - S_0)/(S_2 - S_0)$. The heterogeneous pattern of enhancement can be appreciated from the SER map. Figure 2.4(C) is the MIP image created in the lateral-medial direction from the full set of 60 sagittal slices acquired immediately following contrast injection. The MIP is effective for demonstrating the size, shape, and location of the mass, as well as the multifocal disease distributed in other regions of the breast. What is not appreciated on the MIP is the heterogenous interior of the lesion and the separation between the mass and chest wall. Both are better illustrated on the individual slice image of Figure 2.4(A).

Ultimately, the standard breast MRI examination will likely include both an optimized data acquisition and integrated postprocessing. Computer-aided tools for diagnosis may also contribute to improved performance of breast MRI. Such systems are currently under development and incorporate image registration, parametric analysis, and diagnostic thresholds for detecting and characterizing malignancies. Improvements in performance may also be gained by contrast agents that are longer circulating or specifically targeted to cancer cells.

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3
Setting Up a Breast Magnetic Resonance Imaging Program

Elizabeth A. Morris

Breast magnetic resonance imaging (MRI) programs can be set up and structured in a variety of ways. Much depends on the local environment, which not only includes the patient population and referral patterns, but also the equipment available and demands made on the MRI unit. Nonetheless, there are some commonalities that are found in most programs. The role of the interpreting radiologist is crucial in creating a successful program as this person acts as the pivot. Incorporation of breast MRI into daily workflow can prove challenging as many logistical problems may arise. It can be helpful to be aware of potential problems and issues in advance. These are discussed in this chapter.

1. Patient Issues

Breast MRI patients have issues that are fairly unique and not found in other patients undergoing MRI. When a women finds herself in the MRI suite for an examination of her breasts it is usually because she has a known cancer, has a very high risk for cancer, or has a problem on her mammogram for which she needs further testing. As a result, these patients are anxious and tense. There are several aspects to scheduling and performing the MRI examination that can alleviate this anxiety.

Flexibility in scheduling MRI examinations can go a long way in decreasing anxiety on the part of the patient. The longer the patient has to wait to schedule an MRI examination, the more anxious she will get, especially if she has a known cancer or a problem on the mammogram. If your program has a dedicated breast MRI machine this likely will not be a problem. As we share our equipment with other types of cases, we have found it helpful to designate daily preoperative breast MRI slots to accommodate breast MRI patients. This approach has allowed us to image patients quickly so that weeks do not elapse before the patient has the examination. A perception that breast disease is important and that breast problems pose unique issues can be an important factor in providing quick access to imaging.

Information about the MRI procedure can also help decrease anxiety. Some centers provide patients with fact cards about what to expect before, during, and after the procedure (Table 3.1). Designating a person, such as a nurse or assistant, to inform and counsel patients can be invaluable, if there are resources for such a person. If there are no resources for such a person, this job may fall to the radiologist or referring physician. Counseling can be particularly helpful when women are undergoing MRI examination for the first time. Ensuring that there are no absolute contraindications for MRI, such as pacemaker, tissue expander, cochlear implant, and so forth, before the patient arrives in the MRI suite is helpful. Also, explaining in advance the necessity of injecting contrast avoids explanations at the time of the examination, as well as unearths any prior history of reaction to contrast.

Before the patient undergoes the MRI examination, the patient and the referring physician should possess a clear understanding of potential outcomes. Recognition of the possibility of follow-up MRI and possible biopsy due to findings on the MRI is essential and, it is hoped, avoids drastic clinical decisions such as surgery based on MRI findings alone. Often the patient is sent for MRI examination without the understanding that it is a complementary test that may generate additional testing with ultrasonography or mammography. It is hoped that educating referring physicians and patients alike will correct these misperceptions.

As MRI is an adjunctive test that should complement mammography and is only used in specific clinical situations, patient self-referral for breast MRI should be discouraged. Physician referral can also sometimes be problematic, particularly at the start. It may be helpful initially to designate a single radiologist to screen and protocol all referred breast MRI cases to ensure that the appropriate patients are being scanned. This would include requests from clinicians who may not initially

Table 3.1. Patient Fact Card

Breast MRI

INTRODUCTION

MRI, magnetic resonance imaging, is a diagnostic procedure to view areas of the body without using X-rays. Magnetic fields and radiowaves are used to detect the size and location of tumors using a large, donut-shaped magnet. Breast MRI is used after a mammogram if more detail is necessary because the doctor suspects there may be disease that the mammogram cannot detect. You cannot have a breast MRI if you have a breast tissue expander or cardiac pacemaker.

PREPARATION

- If you have a condition that makes it difficult for you to lie still in an enclosed area (claustrophobia), or if lying on your stomach with your arms stretched out above your head for 30 to 60 minutes without moving is difficult, tell your doctor before the breast MRI so that medication can be prescribed to help ease any discomfort you may have.
- No other preparation is required. You may take your medication(s) as usual.

TIME

The examination takes up to 40 minutes for both breasts.

PROCEDURE

- You will need to take off your jewelry, bra, and any other clothing items that contain metal, such as zippers or metal buttons.
- You will be able to store your belongings in a locker provided for you.
- Do not take any watches or any card with a magnetic strip (such as a credit card) into the MRI machine, as they may not work once exposed to the magnetic field.
- Before your breast MRI, the procedure will be explained to you, and any questions you have will be answered.
- An intravenous line (IV) will be placed in a vein to give you an injection of a contrast medium called gadolinium-DTPA. The contrast makes it possible to see any abnormality in the breast. The IV will be removed at the end of your procedure.
- You will be asked to lie on your stomach on the MRI table. Once you are positioned, it is extremely important that you do not move during the examination. Your breast will be placed into two holes in the table and will be immobilized by compression paddles.
- You may request earphones so that you can listen to music or earplugs to make you more comfortable and to reduce the clicking sound you will hear from the MRI machine.
- You will be able to talk with the MRI technologist at any time during the examination. If you become very uncomfortable in the MRI machine, tell the technologist.

AFTER THE PROCEDURE

- The site where the contrast medium was injected will be covered with an adhesive bandage (Band Aid®).
- A report of the scan will be sent to your doctor within a few days after your test.

understand the importance of careful patient selection. We found it helpful not only to approve all initial cases but also followed up with periodic reminders in the form of a memo to referring physicians about appropriate indications.

2. Personnel Issues

Targeting an MRI technologist who can ensure standardization and quality of the breast MRI examination can be extremely useful. This person should also have interpersonal skills that can decrease the anxiety of the breast MRI patient. The quality of the examination is dependent on patient cooperation so a technologist who can reassure the patient is crucial. Patient movement can render the examination uninterpretable. Additionally, if fat suppression is used, a technologist who knows how to troubleshoot problems can decrease the number of call-backs and repeats that may need to be performed.

It is absolutely essential that the technologist position the breast in the breast coil. It cannot be emphasized enough that the patient is unable to position herself correctly. The technologist must ensure that the breast has been centered in the coil so that artifact is reduced and that the breast is pulled away from the chest wall as much as possible so that the maximum amount of breast tissue is contained within the coil. If the technologist is a man, it may be helpful to have a woman in the department perform this task.

Expert technical support is especially helpful for interventional procedures. For example, during interventional procedures we have found it useful to not only have the MRI technologist for scanning but also have a mammography technologist for positioning, set up, and disposal of materials. If breasts are able to be positioned adequately in the coils, and support personnel are on hand to help with the procedure, simultaneous interventional procedures such as localization or biopsy may be more easily performed.

3. Breast MRI Protocols

Breast MRI is best used for patients with known cancer or those at high risk for developing cancer, therefore not all

patients are candidates. Having a clear list of indications goes a long way in the education of referring clinicians. It may be helpful to have a *point* radiologist who approves all initial examinations until referring clinicians develop a sense of appropriate cases to refer to breast MRI. At the beginning it may be useful to scan patients with known cancers to develop a sense of confidence and build a knowledge base. Also, these patients are likely going to the operating room regardless and any additional information that the MRI examination provides will likely only help them.

To maximize the breast MRI examination using the chosen sequence on your scanner, there will be some necessary training of the technologists and experimenting with the sequence. This is to be expected when starting a new service and may need to be factored into the schedule. Until the process becomes streamlined and second nature to the technologists, monitoring the examinations will most likely be needed. A certain critical caseload may need to be in place until confidence in the reproducibility of the examination is ensured.

Depending on how you choose to perform breast MRI examinations, availability of the radiologist may be an issue. If you choose to perform problem-solving detailed studies in which the protocol may vary depending on the clinical problem, then this will require the radiologist's time. Much of what you choose to do will depend on patient volume and availability of a radiologist.

In our practice, a busy clinical service, streamlining the examination for rapidity and reproducibility without constant monitoring was paramount.

We have found protocols that are fixed and streamlined increase throughput. All of our nonresearch examinations, regardless of the clinical indication, are performed with the same protocol. It is now rare that a radiologist needs to monitor an examination as we try to ensure all necessary information is obtained on every patient via close communication beforehand with the referring clinicians and the MRI technologists.

We have found it helpful to review and protocol each case in advance. This way, we can be sure that the patient has had the appropriate work up to date and that all necessary information is available for the time of interpretation. It can also clarify protocols for implant patients, who might be undergoing both a rupture evaluation and an assessment of the breast parenchyma with intravenous contrast. In these cases, the patient and referring physician need to know that these are two separate examinations with differing imaging protocols.

4. Scheduling Considerations

When performing MRI for breast cancer evaluation, a shift in the traditional MRI schedule may be needed. This can help develop continuous referral from surgical and oncological colleagues. In addition to building in flexibility for preoperative cases, flexibility in scheduling other patients can be important. Evaluation of breast lesions has traditionally moved faster than in other areas of medicine. Breast centers are set up for *same-day* service. Asking a patient to wait 2 weeks for an MRI appointment may be perceived as a long delay even though it may be reasonable in other circumstances.

When deciding how to allot your time on the scanner, it may be helpful to *batch* the breast MRI cases, particularly if you examine women at high risk and have a dedicated screening program. We have found this extremely helpful to have the nonemergent cases come for scanning on the weekend. They are comforted seeing other women undergoing the same examination and are usually not sharing the waiting room with acutely ill hospital patients. Additionally, the MRI technologist can develop a rhythm and increase throughput of patients, making the examination more efficient. The breast coil can be maintained on the table and the infusion pump can be easily refilled.

5. Patient Preparation

Similarly, obtaining detailed clinical information from referring colleagues can make a difference in the interpretation of the breast MRI examination. When the radiologist protocols the examination in advance, additional information can be obtained. Also, when the patient arrives in the MRI suite, the patient and nurse fill out a questionnaire together (Table 3.2). This ensures capture of important information, such as prior surgical history of the breasts, any pertinent family history, and menstrual history.

It is helpful to record the patient's last menstrual period and if the patient takes hormone replacement therapy. We generally do not schedule patients based on their menstrual history if there is an acute problem or if the patient is presurgical. However, if the patient does not have a pressing need, such as our high-risk screening patients, we will make all efforts to schedule in the second week of the menstrual cycle. We have found that educating referring physicians about the menstrual changes that can be seen on MRI has been helpful in eliminating the problem of having to repeat an examination due to menstrual changes. In order to educate the referring physician, our schedulers initially ask the referring physician's office if the patient was premenopausal or postmenopausal and if premenopausal, if she would be in the second week of her cycle. If the schedulers are unable to perform the task, the point radiologist who approves all initial breast MRI examinations can easily inquire about menstrual history.

Scars from prior benign breast biopsies and prior breast conservation, as well as palpable abnormalities, are