Steven E. Harms, MD • Duane P. Flamig, PhD • Kerri L. Hesley, MD • Mark D. Meiches, MD
Richard A. Jensen, MD • W. P. Evans, MD • Daniel A. Savino, MD • Robert V. Wells, MD

MR Imaging of the Breast with Rotating Delivery of Excitation Off Resonance: Clinical Experience with Pathologic Correlation[1]

An investigative study was undertaken to determine the potential for a new magnetic resonance (MR) imaging technique, RODEO (rotating delivery of excitation off resonance), for use as a diagnostic imaging tool for the breast. The RODEO technique provides fat suppression with T1 weighting and is ideal for gadolinium-enhanced breast imaging. It is a short repetition time, steady-state sequence for high-resolution three-dimensional acquisitions and provides a clinically efficient imaging time of approximately 5 minutes for 128 sections. Imaging findings were correlated with serially sectioned pathologic specimens in 30 breasts with 47 malignant and 27 benign lesions. MR imaging had a sensitivity of 94% and a specificity of 37%. MR imaging depicted additional cancers not seen at mammography in 11 of the 30 patients (37%). The lesions not seen at mammography varied in size from 3 mm to 12 cm. RODEO MR imaging may be used to improve diagnosis of breast cancer in patients with mammographically dense breasts or silicone implants/injections and to stage disease in patients who are candidates for lumpectomy.

Index terms: Breast, diseases, 00.72 • Breast neoplasms, MR, 00.31, 00.32 • Gadolinium • Magnetic resonance (MR), contrast enhancement • Magnetic resonance (MR), pulse sequences

Radiology 1993; 187:493–501

[1] From the Departments of Radiology (S.E.H., D.P.F., K.L.H., M.D.M., R.A.J., W.P.E.) and Pathology (D.A.S., R.V.W.), Baylor University Medical Center, 3500 Gaston Ave, Dallas, TX 75246. From the 1992 RSNA scientific assembly. Received August 13, 1992; revision requested September 24; final revision received December 23; accepted December 29. Supported in part by the Susan G. Komen Breast Cancer Foundation, the Helen Buchanan and Stanley Joseph Seeger Endowment for the Fellowship in Breast Oncology, and the Chilton Foundation. **Address reprint requests to** S.E.H.

THE use of magnetic resonance (MR) imaging for the diagnosis of breast cancer is not new. Images of the breast were some of the first produced of any human anatomic part with MR imaging (1,2). MR imaging of the breast was performed as early as 1978, before head images and 4 years before the first commercial imager appeared in 1982 (1).

When commercial MR imaging began, early clinical trials predicted the potential for MR imaging in breast cancer diagnosis (3–6). More detailed clinical studies, however, revealed that MR imaging had little to offer over less expensive and more widely available conventional imaging methods (7).

By the late 1980s, MR imaging of the breast was thought by most experts in the field to have little future (7,8). About the same time, gadopentetate dimeglumine was introduced in Europe. Research with this agent revealed that breast cancer consistently enhanced after administration of gadopentetate dimeglumine and that these enhancing cancers could often be differentiated from some benign lesions (9–11). Most tumors demonstrated rapid contrast enhancement within the first 5 minutes. Because of this rapid enhancement, tumors can be differentiated from normal breast parenchyma. Tumor enhancement was substantially greater than that of breast parenchyma within the first 5 minutes and was nearly equal to that of breast parenchyma at 10 minutes after injection. Scars, sometimes thought to represent cancer on mammograms, did not enhance on MR images (9–13).

In Germany, where surgical biopsy is routine and needle biopsy is seldom used for diagnosis, the use of MR imaging was believed to be of value in prebiopsy imaging to reduce the number of biopsies performed for false-positive mammograms. In countries where needle biopsy is more accepted, the use of MR imaging as the only tool for improving specificity was more difficult to justify, since a needle biopsy is less expensive than MR imaging and provides a definitive histologic diagnosis. In centers where needle biopsy is an accepted alternative to surgical biopsy, major problems remain for the application of MR imaging for routine breast diagnostic management in most clinical situations. Even with use of modern MR imaging techniques with contrast enhancement and conventional fat suppression, investigators found in a recent study that lesions were missed at conventional MR imaging that were seen at mammography (14).

For MR imaging to play a major role in breast cancer management, it must meet several major technologic considerations: (*a*) it must have high resolution (approximately 1-mm resolution in all three planes) for detection of small lesions, (*b*) it should employ fat suppression for differentiation of enhancing tumors from fat, and (*c*) acquisition should be rapid (preferably less than 6 minutes) for differentiation of enhancing tumors from breast parenchyma.

Previous studies have indicated that cancers enhance early and can be best differentiated from benign masses and breast parenchyma in the first 6 minutes after injection of contrast material (9–11). These factors were the incentive for our research in creating a new breast MR imaging technique called RODEO (rotating delivery of excitation off resonance). The purpose of our study was to evaluate this new method with rigorous pathologic correlation and compare

Abbreviations: MIP = maximum intensity projection, MT-FATS = magnetization transfer with fast adiabatic trajectory in the steady state, RODEO = rotating delivery of excitation off resonance, TE = echo time, TR = repetition time.

this method with conventional imaging (ie, mammography, sonography, and galactography).

Fat suppression has a demonstrated value in the identification of contrast-enhancing lesions on T1-weighted images when the surrounding, normally hyperintense fat may obscure the lesion (15–18). Because of the abundance of fat in normal breasts, fat-suppressed imaging is a desirable feature in an imaging protocol designed to detect contrast-enhancing lesions.

A variety of methods are available for producing fat-suppressed images: (*a*) chemical shift (time domain) imaging with four-dimensional Fourier transform techniques (19), (*b*) selective saturation or excitation (20–22), (*c*) phase encoding based on differences in chemical shift evolution between fat and water (23), and (*d*) methods using relaxation differences between fat and water, such as short inversion time inversion recovery (STIR) (24). These techniques require either a long repetition time (TR) pulse sequence or multiple excitations and are not well suited for steady-state (short TR) three-dimensional applications.

A previously used steady-state fat-suppression sequence, MT-FATS (magnetization transfer with fast adiabatic trajectory in the steady state), employs magnetization transfer contrast to suppress the signal intensity of ductal tissue (17). In comparison to the MT-FATS technique, RODEO provides more T1 weighting, uses a shorter TR for an approximately 50% reduction in imaging time, and has fewer artifacts because of the elimination of the magnetization transfer preparation pulse.

MATERIALS AND METHODS

General Technical Features

MR imaging was performed with a Signa imager (GE Medical Systems, Milwaukee, Wis) operating with 4X software at 1.5 T. Image reformations and maximum intensity projection (MIP) ray tracings were performed with an independent console (GE Medical Systems).

A prototype linear radio-frequency (RF), transmit-receive breast coil (Medrad, Pittsburgh, Pa) was developed specifically for MR imaging of the breast. For all examinations, the patients were imaged in the prone position without breast compression.

Three-dimensional imaging was performed to improve the image resolution and facilitate image processing methods. The display matrix of 128 × 256 × 256 produces voxel resolution of about 1.4 × 0.7 × 0.7 mm for an 18-cm field of view. The sagittal, coronal, and axial images were reformatted with the same set of image data. The use of the image-processing workstation allows near real-time reformations to facilitate the depiction of oblique imaging planes. The high-signal-intensity breast nodules within the entire volume can be demonstrated with MIP ray tracing.

This method allows considerable flexibility in viewing possible anatomic defects. Multiple-angle, fast reformations allow the reader to follow questionable lesions to determine the identity of the lesion, whether vessel or mass, and the relationship of the defect to other structures. The MIP methods provide a quick survey of disease extent and anatomic relationships.

Pulse Sequence

A steady-state fat-suppressed sequence was developed to achieve optimal image contrast for T1-weighted three-dimensional imaging of the breast (Fig 1). RODEO uses a sine excitation on fat resonance followed by a similar sine excitation 180° phase shifted. The second excitation drives fat magnetization back longitudinally (aligned with the applied magnetic field), resulting in suppression of fat on the image. Because water is off resonance for both excitations, both RF pulses are additive for water resonance to result in transverse magnetization that produces MR signals. The RODEO method can be achieved with a very short TR (18.5 msec) and echo time (TE) (3.9 msec) and one excitation for efficient three-dimensional acquisition of approximately 5 minutes.

Fluids with long T2s had high signal intensity, even on T1-weighted images produced with steady-state fast imaging pulse sequences. RF spoiling is a technique that randomizes the phase of the digital RF to reduce the signal intensity resulting from the long T2 steady state. The RF spoiling technique was used to depict lesions with a high fluid content. The precontrast images were obtained without RF spoiling. The RODEO images obtained without RF spoiling demonstrated high-signal-intensity fluid resulting from the steady-state buildup on long T2 spins. The postcontrast images were obtained with RF spoiling to reduce the signal intensity of lesions with a high free-fluid content.

With the variable use of RF spoiling, cysts and masses had the opposite appearance on the pre- and postcontrast images. On precontrast images, cysts had high signal intensity and masses had low signal intensity. On postcontrast images, masses had high signal intensity and fluid-filled lesions had low signal intensity as a result of RF spoiling.

Patient Studies

Eighty-eight breasts were imaged at our institution with RODEO MR imaging and mammography. Patients entering the study had a high suspicion for breast cancer on the basis of clinical findings or conventional imaging studies. Other imaging studies, such as galactography and sonography, were performed as clinically warranted. The patients ranged in age from 32 to 87 years (mean, 56 years). Of the patients who underwent RODEO MR imaging, 30 underwent mastectomy with pathologic analysis of serial sections.

To visualize the early-enhancement features of cancer, MR images were obtained immediately after intravenous injection of 0.1 mmol/kg (usually 8–16 mL) of gadopentetate dimeglumine. To ensure consistent contrast timing, gadopentetate dimeglumine was given at the manufacturer-recommended maximum rate of 10 mL/min beginning at the start of tuning and ending during the initial image data collection.

Pathologic Analysis

To accurately correlate the MR imaging and pathologic findings, the patient's skin was marked for longitudinal axis before MR imaging. Images were reformatted along the marked axis at 5-mm intervals and were analyzed with the workstation for comparison with the pathologic specimen. The mastectomy specimens were frozen and sectioned along the marked

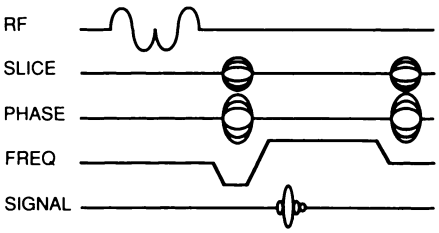
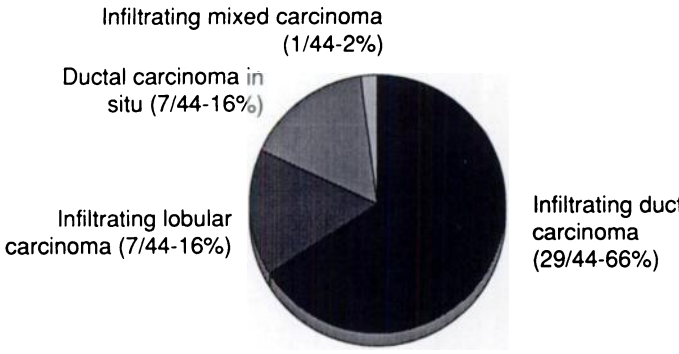


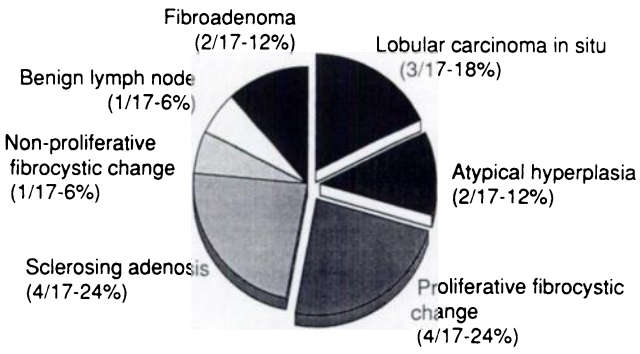
Figure 1. Pulse sequence diagram for the RODEO technique. To improve the fat suppression and T1 contrast of steady-state three-dimensional acquisitions, two new pulse sequences were developed. RODEO is a new pulse sequence that employs a jump return sine excitation on fat resonance to produce fat-suppressed, T1-weighted images. *FREQ* = frequency.

Table 1
Lesions Identified in Breasts with Pathologic Correlation

Parameter	Findings	
	MR Imaging	Conventional Imaging
True-positive cases	44	26
False-positive cases	17	3
True-negative cases	10	24
False-negative cases	3	21
Sensitivity (%)	94	55
Specificity (%)	37	89
Accuracy (%)	73	67

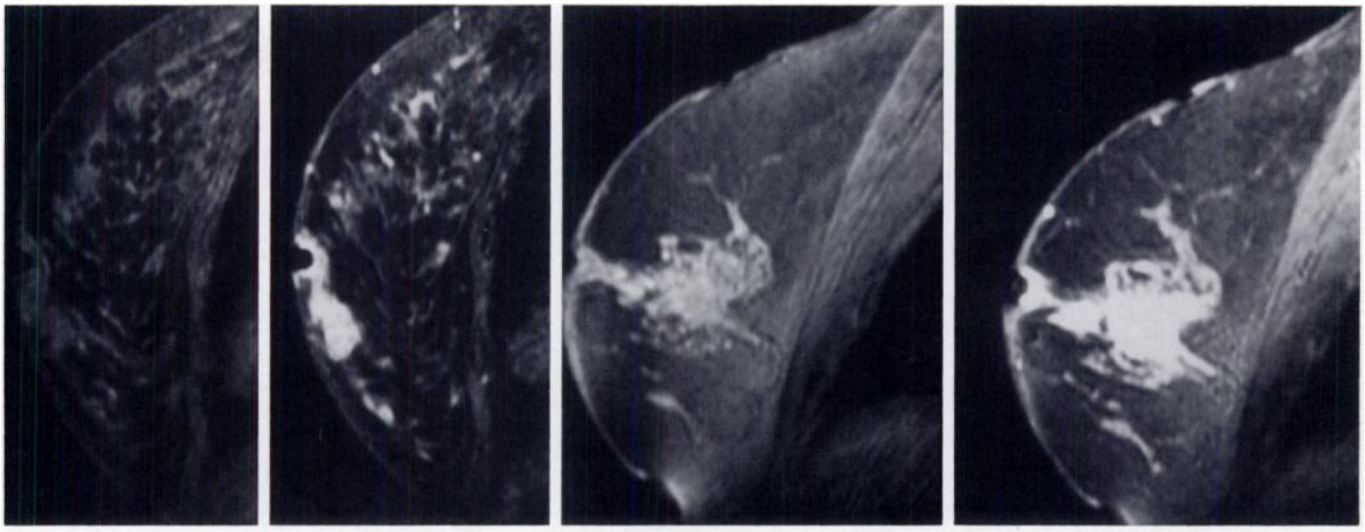


2.



3.

Figures 2, 3. Pie charts illustrate characteristics of true-positive **(2)** and false-positive **(3)** lesions.



a. **b.** **c.** **d.**

Figure 4. Nipple enhancement. The nipple normally enhances with contrast material. **(a, b)** An example of nipple enhancement histologically confirmed as normal is shown in a 51-year-old woman with sagittal reformatted RODEO MR images (TR msec/TE msec = 18.5/3.9) obtained before **(a)** and after **(b)** administration of gadopentetate dimeglumine. The mass adjacent to the nipple was an infiltrating lobular carcinoma with ductal carcinoma in situ. Because of the proximity of enhancement to the nipple, the nipple was incorrectly interpreted as involved by tumor. **(c, d)** RODEO MR images (18.5/3.9) obtained in a 65-year-old patient with histologically confirmed infiltrating ductal carcinoma involving the nipple, which was incorrectly interpreted as normal nipple enhancement. Sagittal reformatted images obtained before **(c)** and after **(d)** administration of gadopentetate dimeglumine demonstrate a finger of enhancement extending from the adjacent mass, an infiltrating ductal carcinoma.

longitudinal axes by using 5-mm-thick sections.

The pathologists and radiologists jointly evaluated the tissue slices and compared each slice with the corresponding MR image. Thus, lesions that could not be seen or palpated on the pathologic section could be sampled for histologic examination. The extent of the enhancing lesion identified at MR imaging was directly correlated with the extent of histologic abnormality. The tissue slices and the grossly apparent lesion margins were traced onto tissue paper to estimate lesion size. Size estimates for smaller lesions were obtained microscopically. In patients who did not undergo mastectomy, the histologic characteristics of the primary lesion were obtained with lumpectomy, excisional biopsy, or needle biopsy.

Image Analysis

A lesion was defined as positive at MR imaging if its signal intensity was higher than that of breast parenchyma on postcontrast images. There was no attempt to further categorize lesions on the basis of morphologic appearance (ie, whether they were spiculated, speckled, well defined, or ill defined).

Two independent observers (R.A.J., M.D.M.) evaluated the MR images without prior knowledge of patient history or results of mammography. Abnormal enhancement was categorized as either diffuse or focal. Diffuse enhancement was defined as ill-defined abnormal enhancement interspersed throughout the breast parenchyma or multiple focal nodules (3–10 mm in diameter) extending throughout the breast parenchyma. The size and number of the enhancing focal lesions were determined by the independent observers.

Conventional imaging was performed at one dedicated mammographic imaging center. All mammograms were interpreted with knowledge of all associated clinical information by one observer (W.P.E.). All mammographically suspicious entities, including spiculated masses, microcalcifications, asymmetric opacities, and diffuse microcalcifications were considered positive.

Histologically positive lesions (cancer) included intraductal carcinoma, infiltrative ductal carcinoma, lobular carcinoma, and mixed carcinoma. Results were classified as true-positive if there was a positive imaging study of a histologically positive lesion. Results were classified as false-negative if a histologically positive lesion was either not identified or identified as benign at imaging. A histologically negative lesion was a lesion identified either with MR imaging or mammography that was not malignant (intraductal carcinoma, infiltrative ductal carcinoma, lobular carcinoma, or mixed carcinoma). A positive imaging study with negative histologic findings was considered to be false-positive. Results were classified as true-negative if a histologically negative lesion was either interpreted as benign or not seen at imaging.

Benign changes seen only at pathologic examination were noted but were not considered a true-negative finding. Nonproliferative fibrocystic change encountered only with histologic sectioning without identification at MR imaging or mammography were not considered a true-negative finding. If proliferative fibrocystic change corresponded to an area of high signal intensity on MR images and was not seen at mammography, it was considered a false-positive finding for MR imaging and a true-negative finding for mammography.

RESULTS

The clinical and diagnostic imaging data from the 30 breasts with pathologic correlation are summarized in Table 1. Seventy-four lesions were detected: 47 were malignant and 27 were benign. There was no disagreement in the MR imaging observations of all 47 histologically positive lesions (44 true-positive cases and three false-negative cases). Reviewers disagreed in four cases. All of the discrepant lesions were false-positive, and the larger number of lesions (either reviewer) was used for statistical analysis in all cases.

The histologic characteristics of the true-positive and false-positive lesions are summarized in Figures 2 and 3. Focal cancers (n = 47) ranged from 3 mm to 12 cm in diameter, with a mean of 2.6 cm and a median of 2 cm. Lesions missed with mammography ranged from 3 mm to 12 cm in diameter, with a mean of 2.5 cm and a median of 1.4 cm.

Of the 30 breasts examined pathologically, 29 had evidence of cancer. The one case with no evidence of cancer (false-positive finding at MR imaging and mammography) had a fibroadenoma and atypical ductal hyperplasia. The distribution of cancers in the 29 positive breasts at pathologic examination is summarized in Table 2. Diffuse enhancement was identified at MR imaging in six breasts. Of those six breasts, four cases corresponded pathologically to diffuse carcinoma, while the other two cases were focal carcinomas. Mammography was positive in only three of those six cases.

Mammography combined with sonography depicted no cancers that were not also depicted with MR imaging. MR imaging depicted cancers not seen at mammography (solitary and multicentric disease) in 11 of the 30 serially sectioned breast specimens (37%). Two false-negative MR findings occurred with nipple involvement that was interpreted on MR images as normal nipple enhancement.

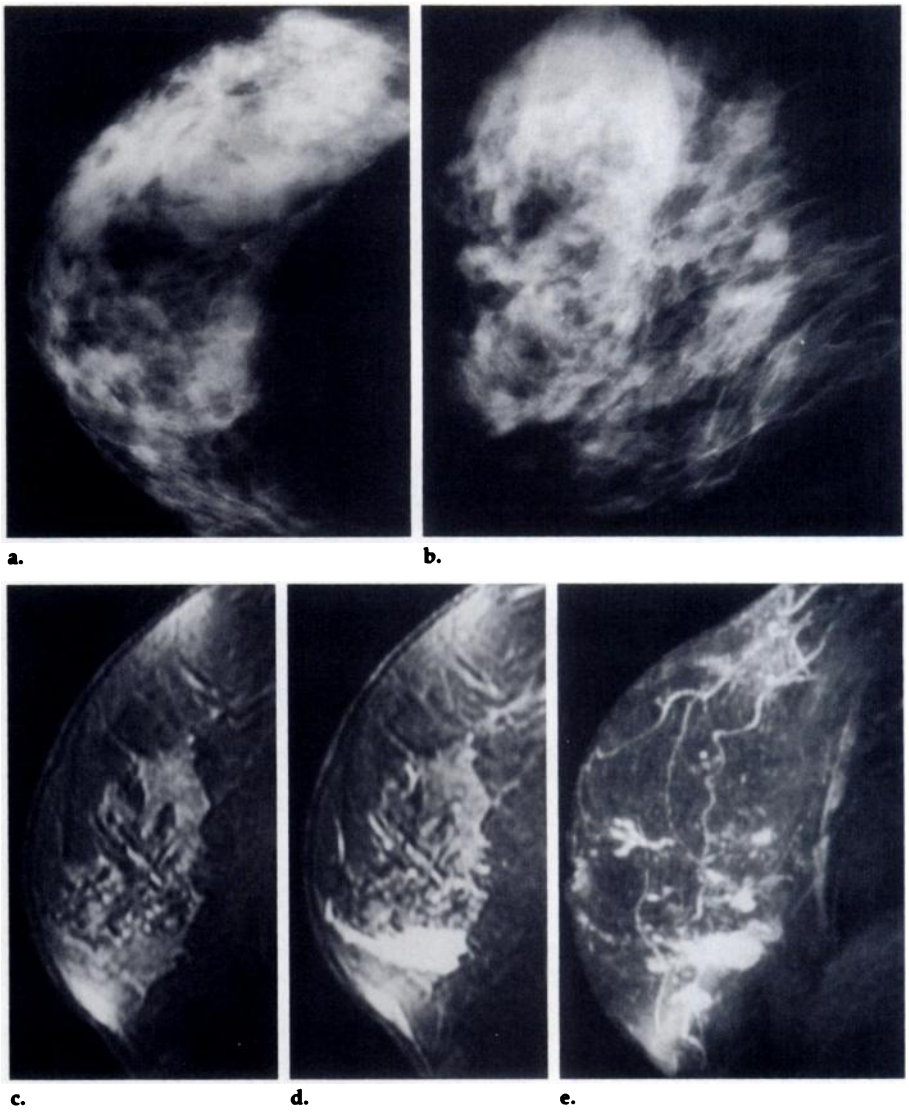
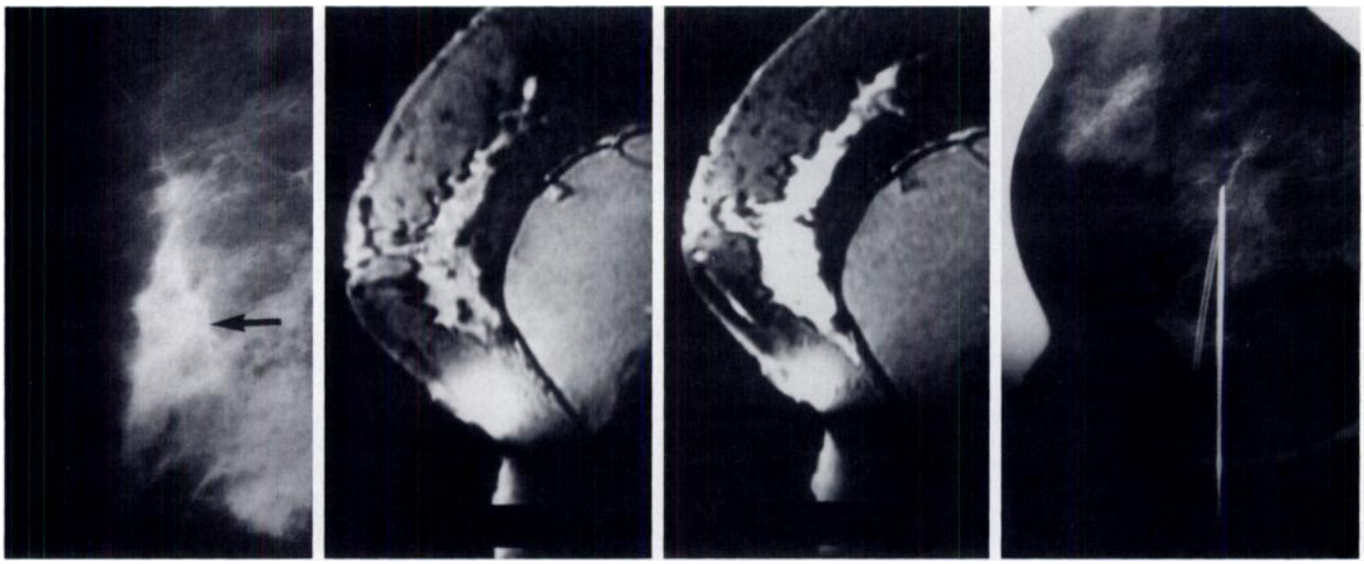


Figure 5. Infiltrating ductal carcinoma in a postmenopausal patient. A 68-year-old woman presented with a lump in her axilla, which was sampled for biopsy and determined to be a lymph node with metastatic adenocarcinoma. Craniocaudal **(a)** and mediolateral oblique **(b)** mammograms demonstrate no evidence of a focal mass. A metastatic work-up revealed no primary tumor elsewhere in the body. Calculated sagittal RODEO MR images (18.5/3.9) obtained before **(c)** and after **(d)** administration of gadopentetate dimeglumine demonstrate a large, irregularly marginated, enhancing mass in the inferior aspect of the breast. The mediolateral projection image **(e)**, calculated with the same RODEO image data, shows the mass relative to the entire breast. At histologic examination, this mass was found to be infiltrating ductal carcinoma. MR imaging may play a role in the diagnosis of cancer in postmenopausal women with a high suspicion of cancer but negative findings at conventional imaging examinations.

In these cases, positive MR findings were present elsewhere in the breast and, in retrospect, nipple involvement was also present on the MR image (Fig 4). The other false-negative MR finding was malignant involvement of an intramammary lymph node that did not substantially enhance with contrast material, possibly because of microscopic tumor that did not result in substantial enhancement relative to normal components of the lymph node.

The histologic characteristics of lesions that were false-positive at MR imaging are summarized in Figure 3. Although these lesions are not considered neoplastic, some are associated with a higher frequency of malignancy.

All forms of breast carcinoma consistently enhanced with contrast material. The fat-suppressed three-dimensional imaging method demonstrated previously unidentified lesions in two women with mammographically dense breasts. MR imaging demonstrated cancer in the breast of a postmenopausal woman with a positive axillary lymph node but negative findings at mammography (Fig 5). MR imaging showed abnormal en-



a. b. c. d.

Figure 6. Improved definition of lesion borders with MR imaging. **(a)** Mammogram obtained in a 55-year-old woman with silicone augmentation implants and no palpable masses shows a focal area of architectural distortion (arrow) with Eklund view. Magnification mammography demonstrated two closely approximated areas suspicious for disease with subtle microcalcifications. The patient was considered a candidate for lumpectomy. **(b, c)** Sagittal RODEO MR images (18.5/3.9) obtained before **(b)** and after **(c)** administration of gadopentetate dimeglumine and before lumpectomy reveal diffusely abnormal enhancement throughout the ductal tissue, involving all four quadrants. **(d)** The area identified mammographically was localized, and lumpectomy was performed. Lumpectomy demonstrated cancer extending to all margins of the specimen. Subsequent mastectomy showed infiltrative ductal carcinoma corresponding to the areas of abnormal enhancement demonstrated on the MR images. If the MR imaging information had been used clinically, the patient could have avoided unnecessary lumpectomy. The more accurate definition of tumor borders with MR imaging may improve the preoperative assessment by defining the extent of lumpectomy needed for local disease control. An MR image was obtained of her other breast, which had no mammographically defined abnormality or palpable masses. The opposite breast demonstrated an MR imaging appearance similar to that of the breast shown, with abnormal enhancement extending throughout the breast parenchyma. Blind biopsy of the breast demonstrated infiltrating ductal carcinoma. Analysis of the mastectomy specimen correlated cancer exactly with the signal intensity abnormalities shown on MR images.

hancement representing carcinoma in two patients with palpable masses but negative findings at mammography. MR imaging depicted a focus of enhancement in three patients in whom the only mammographic finding was an asymmetric opacity.

In 33 of 47 histologically confirmed carcinomas, the MR imaging–determined tumor size correlated more closely with the pathologically determined tumor size than did the mammographically determined size (Fig 6). In 11 malignancies, MR imaging and mammography were similar in the evaluation of tumor size. In no case was mammography more accurate in the determination of tumor size than MR imaging.

In three of the 47 malignancies determined pathologically, all imaging techniques failed to depict the lesion. Two of five cases of lobular carcinoma were negative at mammography. In the other three cases, the abnormalities were underestimated at mammography. All lobular carcinomas were well demonstrated on MR images, with accurate depiction of lesion extent.

Multicentric disease was defined as multiple true-positive lesions in the same breast. MR imaging and pathologic analysis demonstrated multicentric disease in 12 breasts in 11 patients (Fig 7; Table 2). In patients with multicentric disease, results of mammography were negative in three of 12 breasts, solitary lesions were diagnosed in seven, and diffuse disease was diagnosed in two. In the two patients with evidence of diffuse disease at mammography, RODEO MR imaging showed diffuse enhancement, which was confirmed as diffuse carcinoma at pathologic examination.

In the 10 breasts with discrepant findings at MR imaging and mammography and pathologic evidence of multicentric disease, cancer was identified with MR imaging in the same quadrant in three of the 10 breasts, in two quadrants in four breasts, and in more than two quadrants in three breasts. In one case, infiltrating lobular and infiltrating ductal carcinoma occurred in the same breast. The size of the additional foci not seen at mammography varied from 3 mm to 12 cm. In the multifocal disease not categorized as diffuse, the average size of the lesions missed at mammography was 20 mm.

In five cases, MR imaging was performed before and after a preoperative course of chemotherapy. MR imaging accurately depicted the cancers on all image sets. The postchemotherapy images demonstrated reduction in the enhancing parenchyma that was correlated with the extent of disease by means of pathologic analysis of serial sections in one case. A reduction of mass at MR imaging documented a response to chemotherapy that was confirmed with lumpectomy in four cases. These studies demonstrated the potential of MR imaging to define chemotherapeutic response.

Benign lesions, such as fibroadenoma and sclerosing adenosis (Fig 8), may be difficult to distinguish from malignancies on the basis of enhancement alone. Although areas of fibrocystic change usually do not enhance with contrast material, enhancement did occur in one case. However, areas of proliferative fibrocystic change had abnormal enhancement in three cases.

Many benign lesions that were only seen at pathologic analysis did not enhance with contrast material. These lesions consisted of fibroadenoma, areas of nonproliferative fibrocystic change, and areas of proliferative fibrocystic change.

Among the patients who did not undergo analysis of serially sectioned mastectomy specimens, histopatho-

logic findings were not available in 12, and four were lost to follow-up. A statistical summary of the histopathologic characteristics of breasts not subjected to pathologic analysis is given in Table 3. Review of the biopsy results was useful for demonstrating the ability of MR imaging to exclude malignancy. There were no biopsy-confirmed cases of nonenhancing lesions on MR images that were histologically positive (false-negative cases). Biopsy-confirmed lesions that were positive at mammography and did not enhance at MR imaging included postoperative scar ($n = 1$), radial scar ($n = 1$), fat necrosis ($n = 1$), and silicone leak ($n = 2$).

DISCUSSION

With advances in the early detection of breast cancer comes the potential for breast-conserving surgery. The selection of candidates for breast-conserving surgery is dependent on the determination of disease extent with clinical and imaging studies (25–28). A highly sensitive imaging tool should play an important role in the staging of candidates for breast-conserving surgery.

In patients with clinically occult, nonpalpable breast cancers detected at mammography, the frequency rate of multicentric disease varies from 44% to 60% (29–32). The potential for failure of breast conservation treatment because of marked "subclinical" disease has been demonstrated (33–34). The evaluation of patients with an imaging method that is sensitive to undetected multicentric disease could have a major effect on breast cancer treatment.

The RODEO method helped detect additional cancers in 37% of the patients and had a sensitivity for cancer detection of 94%. The improved sensitivity of this method could be used to define marked multifocal disease in patients who are candidates for lumpectomy. The major drawback of MR imaging in this role was the inability to accurately distinguish normal nipple enhancement from nipple involvement by carcinoma in two patients. The presence of tumor in the nipple usually eliminates the opportunity for breast-conserving surgery.

Because of its ability to more accurately depict tumor margins, RODEO MR imaging could be used to more effectively plan lumpectomy surgery. Tumor may extend to the margin of

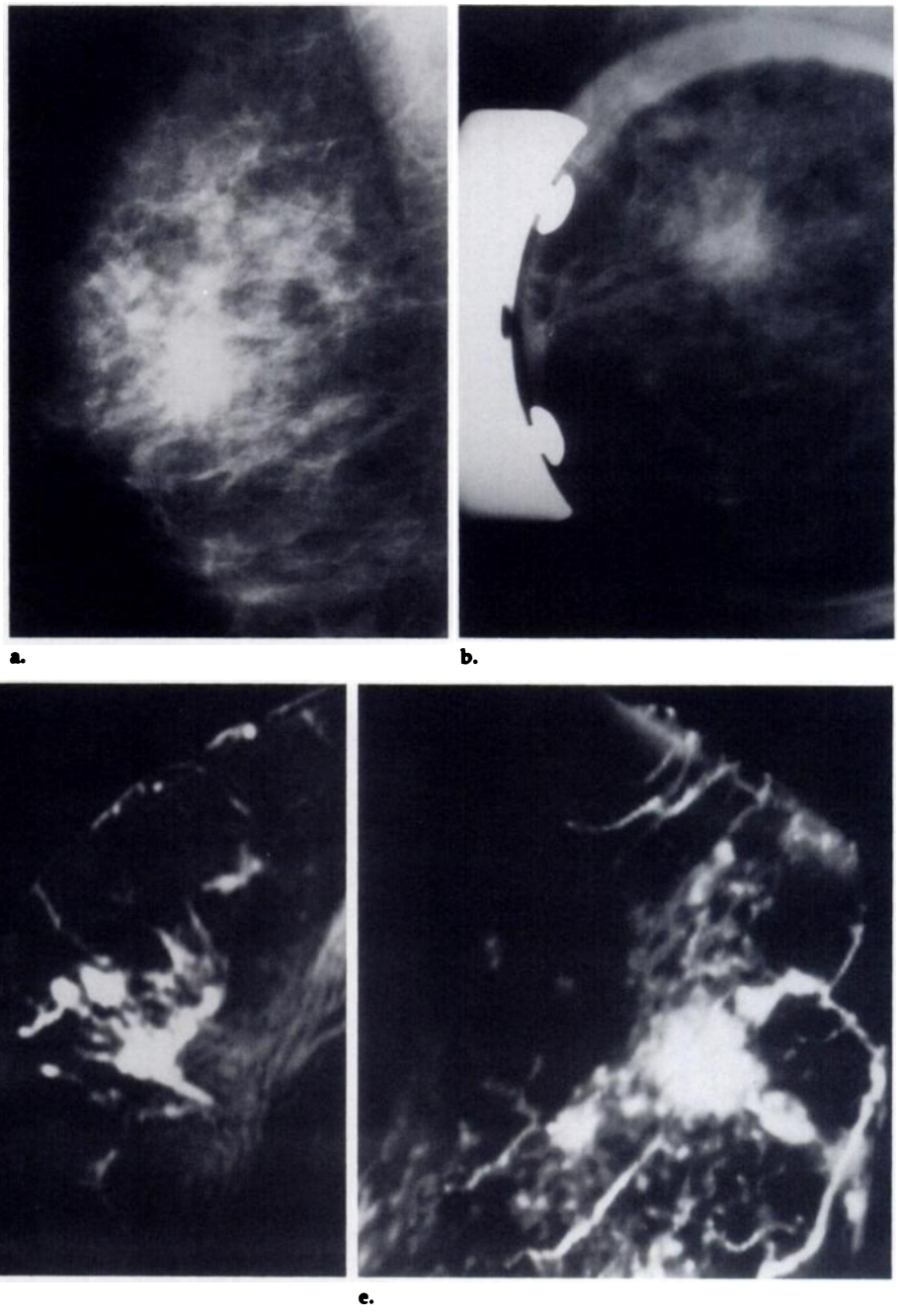


Figure 7. Multifocal carcinoma identified at MR imaging in a patient with presumed unifocal disease at mammography. A focal area of architectural distortion is seen on the mediolateral oblique **(a)** and magnification **(b)** mammographic views. Sagittal reformatted RODEO MR images obtained before **(c)** and after **(d)** administration of gadopentetate dimeglumine demonstrate three irregularly marginated areas of abnormal contrast enhancement. Mediolateral MIP projection image **(e)** demonstrates all three masses and their relationships to the nipple.

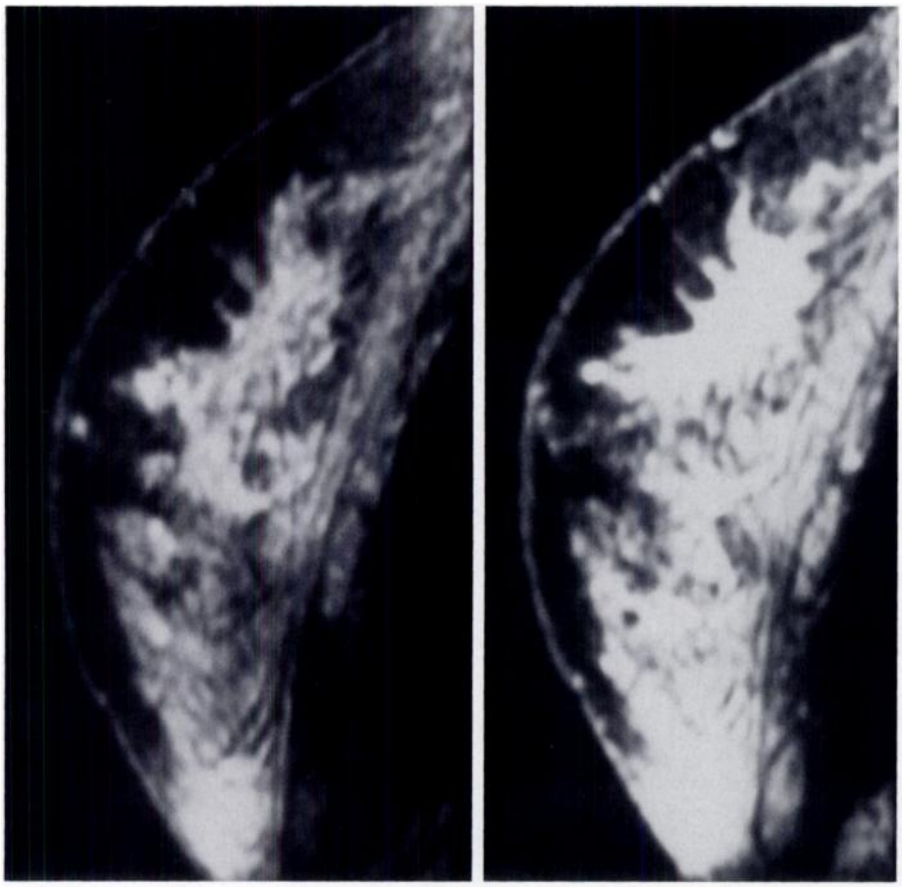
the excised tissue, which would require repeat surgery to excise the remaining tumor. The use of the RODEO technique may reduce the need for repeat excision surgery for tumor extending to the margin of the lumpectomy site.

Perhaps the greatest dilemma encountered with high-resolution MR imaging of the breast is the lack of specificity (37%). The false-positive studies consisted of lesions associated with an increased risk of malignancy, such as lobular carcinoma in situ, atypical hyperplasia, and areas of fibrocystic change. These lesions composed 53% of the false-positive MR imaging diagnoses.

Table 2
Distribution of Cancers in the 29 Positive Breasts with Pathologic Correlation

No. of Cancers Detected per Breast	Findings		
	Pathologic Examination	Mammography	MR Imaging
None	0	3	0
1	17	24	17
2 in the same quadrant	2	0	2
2 in multiple quadrants	4	0	4
More than 2 in same quadrant	1	0	1
More than 2 in multiple quadrants	1	0	1
Diffuse	4	2	4
Total	29	29	29

Note.—Data are numbers of breasts.



a. **b.**

Figure 8. False-positive diagnosis at MR imaging. Reformatted sagittal RODEO MR images obtained before **(a)** and after **(b)** administration of gadopentetate dimeglumine demonstrate an irregularly marginated area of contrast enhancement, which was found to represent sclerosing adenosis at histologic examination. Although most cases of enhancement in sclerosing adenosis and fibroadenoma were well-defined lesions, irregular enhancement occurs and cannot be distinguished from carcinoma.

Other clearly benign conditions that enhanced at MR imaging were sclerosing adenosis and fibroadenoma. All cases of sclerosing adenosis that were identified pathologically were identified at MR imaging as enhancing lesions. Many fibroadenomas that did not enhance at MR imaging were found at pathologic analysis of serial sections. To our knowledge, the lack of enhancement of fibroadenomas has not previously been reported. The discovery of nonenhancing fibroadenomas is a direct result of the rigorous pathologic analysis performed in this study.

Previous studies used pathologic correlation of surgical biopsies and lumpectomies (9–14,17). That correlation was limited to lesions that could be seen with mammography or felt by the surgeon and also excluded the possibility of pathologically detecting lesions not seen at mammography. The results of such analyses led to a low number of false-negative cases and misrepresentation of the sensitivity of the examination.

The application of MR imaging in the clinical management of breast cancer will require a more accurate determination of the histologic characteristics of the lesions than is provided with the current methods. The MR imaging determination of the rate of contrast enhancement of a lesion after injection of a bolus of contrast material has been proposed as a method for differentiating between fibroadenoma and cancer. Cancers were shown to have an early enhancement pattern, whereas fibroadenomas enhanced later (9–11). It is likely that overlap in patterns will exist between the early- and late-enhancing groups. As can be seen in this study, some fibroadenomas enhance early. It is questionable whether this method can help differentiate between sclerosing adenosis, which consistently enhances early, and invasive carcinoma.

In our study, a positive lesion was defined as one that enhanced at imaging. There was no attempt to further categorize lesions on the basis of morphologic characteristics. The specificity of MR imaging probably could be increased if the morphologic features of the lesions, such as well-defined or spiculated configurations (similar to the categorization used in mammography), were considered. The specificity of mammography defined in this study does not correlate with the specificity reported in larger, less biased studies (35,36). The high specificity of conventional imaging was at-

tributed to the study design, in which candidates were selected for MR imaging on the basis of a likelihood of mastectomy determined by means of clinical or mammographic findings. The use of morphologic criteria considerably improves the specificity of mammographic interpretation. However, as demonstrated in Figure 8, absolute differentiation between benign and malignant disease at MR imaging is unlikely, even when using morphologic criteria.

Histologic diagnosis is usually established with biopsy. Core needle biopsies have become a recognized tool for establishing the histologic diagnosis. In centers where core needle biopsy is not performed and surgical biopsy is the only recognized method for biopsy, MR imaging has been proposed as a useful method for reducing the number of surgical biopsies with negative findings that result from the large number of false-positive mammograms (9–12). Surgical biopsies are expensive, require an incision resulting in scar, and have an associated complication risk. Because MR imaging can help differentiate certain benign lesions such as postoperative scar and fat necrosis from cancer on the basis of enhancement, it may play an important role and can effectively reduce the number of surgical biopsies performed.

The major competition for MR imaging in the role of improving the specificity of mammography is needle biopsy. Positive findings at mammography can be investigated with core needle biopsy, which provides histologic information at a fraction of the cost of MR imaging. It is unlikely that MR imaging will play a major role in cancer diagnosis if improved specificity is the only objective. For MR imaging to be successful, it must be used to improve the sensitivity for detecting lesions that cannot be visualized at mammography.

The combination of a dedicated transmit-receive volume coil with the three-dimensional RODEO pulse sequence gives the maximum efficiency for fat suppression and high-resolution, high signal-to-noise ratio, three-dimensional imaging of the breast. Multicoil arrays have been proposed as a method of increasing image quality. The multicoil arrays are receive-only and require the use of slab selection to limit the field of view to avoid aliasing effects. Slab selection limits the excited volume, requires a longer TE and TR, and increases the total imaging time. Because the RODEO technique cannot be used with receive-only coils, other less efficient methods outlined previously would be the only options for multicoil arrays. A transmit-receive volume coil can be made quadrature, which could increase the signal-to-noise ratio. Currently, the coils in a multicoil array are linear, with no prospect for being made quadrature. The signal-to-noise ratio and homogeneity of multiple coils only approaches that of a true volume coil and can never be better. Finally, all current MR systems can use volume coils, whereas multicoil array technology requires the expense of considerable hardware improvements.

The establishment of histologic characteristics of lesions in abnormalities depicted on MR images but not on mammograms will require the use of MR imaging–directed biopsy. Unfortunately, a device for stereotaxic biopsy with MR imaging guidance is not commercially available. Because of the critical timing issues in lesion enhancement, pliability of the breast, and lack of inherent fixed references, freehand needle guidance has little chance of success.

The greatest problem with the clinical application of MR imaging for improving the sensitivity of the imaging diagnosis of breast cancer is the presence of abnormal enhancement in areas that cannot be detected with conventional methods of diagnosis (mammography and clinical examination). Because of the high rate of false-positive findings with MR imaging, the improvement in sensitivity will be difficult to realize clinically until the advent of MR imaging–guided stereotaxic biopsy. Stereotaxic biopsy will be necessary to differentiate between false-positive enhancement and cancer. Because of this dilemma, MR imaging will play a limited role in breast cancer staging until MR imaging–directed stereotaxic biopsy is available. ■

Table 3
Lesions Identified in Breasts without Pathologic Correlation

Parameter	Finding	
	MR Imaging	Mammography
True-positive cases	21	19
False-positive cases	11	14
True-negative cases	5	4
False-negative cases	0	0

Acknowledgment: We thank Cindy Kitch for her assistance in the implementation of this study and the preparation of this manuscript.

References

1. Bovee WM, Creyghton JH, Getreuer KW, et al. NMR relaxation and images of human breast tumours in vitro. Philos Trans R Soc Lond [Biol] 1980; 289:535–536.
2. Mansfield P, Morris PG, Ordidge R. Carcinoma of the breast imaged by NMR. Br J Radiol 1979; 52:242–243.
3. El Yousef SJ, Alfidi RJ, Duchesneau RH, et al. Initial experience with nuclear magnetic resonance (NMR) imaging of the human breast. J Comput Assist Tomogr 1983; 7:215–218.
4. El Yousef SJ, Duchesneau RH, Alfidi RJ, Haaga JR, Bryan PJ, LiPuma JP. Magnetic resonance imaging of the breast: work-in-progress. Radiology 1984; 150:761–766.
5. El Yousef SJ, Duchesneau RH. Magnetic resonance imaging of the human breast: a phase I trial. Radiol Clin North Am 1984; 22:859–868.
6. Stelling CB, Wang PC, Lieber A, Mattingly SS, Griffen WO, Powell DE. Prototype coil for magnetic resonance imaging of the female breast: work-in-progress. Radiology 1985; 154:457–462.
7. Kopans DB. Breast imaging. Philadelphia, Pa: Lippincott, 1989.
8. Turner DA, Alcorn FS, Adler YT. Nuclear magnetic resonance in the diagnosis of breast cancer. Radiol Clin North Am 1988; 26:673–687.
9. Kaiser WA, Zeitler E. MR imaging of the breast: fast imaging sequences with and without Gd-DTPA. Radiology 1989; 170: 681–686.
10. Heywang SH, Wolf A, Pruss E, Hilbertz T, Eiermann W, Permanetter W. MR imaging of the breast with Gd-DTPA: use and limitations. Radiology 1989; 171:95–103.
11. Stack JP, Redmond OM, Codd MB, Dervan PA, Ennis JT. Breast disease: tissue characterization with Gd-DTPA enhancement profiles. Radiology 1990; 174:491–494.
12. Heywang SH, Hibertz T, Beck R, Bauer WM, Eiermann W, Permanetter W. Gd-DTPA enhanced MR imaging of the breast in patients with post-operative scarring and silicon implants. J Comput Assist Tomogr 1990; 14:348–356.
13. Beck R, Heywang SH, Eiermann W, Permanetter W, Lissner J. Kontrastmittelaufnahme der mamille bei kernspintomographie der mamma mit Gd-DTPA. Digitale Bilddign 1987; 7:167–169.
14. Rubens D, Totterman S, Chacko AK, et al. Gadopentetate dimeglumine-enhanced chemical-shift MR imaging of the breast. AJR 1991; 157:267–270.
15. Simon SH, Szumowski J. Chemical shift imaging with paramagnetic contrast material enhancement for improved lesion depiction. Radiology 1989; 171:539–543.
16. Tien RD, Hesselink JR, Chu PK, Szumowski J. Improved detection and delineation of head and neck lesions with fat suppression spin echo MR imaging. AJNR 1991; 12:19–24.
17. Pierce WB, Harms SE, Flamig DP, Griffey RH, Evans WP, Hagans JE. Gd-DTPA enhanced MR imaging of the breast: a new fat suppressed three-dimensional imaging sequence. Radiology 1991; 181:757–763.
18. Harms SE, Flamig DP, Griffey RA. Three-dimensional imaging. In: Higgins CB, Hricak H, Helms CA, eds. Magnetic resonance

imaging of the body. 2nd ed. New York, NY: Raven, 1992; 199–215.
19. Maudsley AA, Hilal SK, Perman WH, Simon HE. Spatially revolved high resolution spectroscopy by "four dimensional" NMR. J Magn Reson 1983; 51:147–151.
20. Frahm J, Haase A, Hanickle W, Matthaei D, Bonsdorf H, Helzel T. Chemical shift selective MR imaging using a whole-body magnet. Radiology 1985; 156:441–444.
21. Hasse A, Frahm J. Multiple chemical shift selective NMR imaging using stimulated echoes. J Magn Reson 1985; 64:94–102.
22. Keller PJ, Hunter WW, Schmalbrock P. Multisection fat-water imaging with chemical shift selective presaturation. Radiology 1987; 164:539–541.
23. Dixon WT. Simple proton spectroscopic imaging. Radiology 1984; 153:189–194.
24. Bydder GM, Steiner RE, Blumgart LH, Khenia S, Young IR. Imaging of the liver using short TI inversion recovery sequences. Comput Assist Tomogr 1985; 9:1084–1089.
25. Fisher B, Redmond C, Poisson R, et al. Eight-year results of a randomized clinical trial comparing total mastectomy and lumpectomy with or without irradiation in the treatment of breast cancer. N Engl J Med 1989; 320:822–828.
26. Veronesi U, Banfi A, Del Vecchio M, et al. Comparison of Halsted mastectomy with quadrantectomy, axillary dissection, and radiotherapy in early breast cancer: long-term results. Eur J Cancer Clin Oncol 1986; 22:1085–1089.
27. Sarrazin D, Le MG, Arriagada R, et al. Ten-year results of a randomized trial comparing a conservative treatment to mastectomy in early breast cancer. Radiother Oncol 1989; 14:177–184.
28. Blichert-Toft M, Brincker H, Andersen JA, et al. A Danish randomized trial comparing breast-preserving therapy with mastectomy in mammary carcinoma: preliminary results. Acta Oncologica 1988; 27:671–677.
29. Rosen PP, Fracchia AA, Urban JA, Schottenfeld D, Robbins GF. "Residual" mammary carcinoma following simulated partial mastectomy. Cancer 1975; 35:739–747.
30. Holland R, Veling SHJ, Mravunac M, Hendriks JHCL. Histologic multifocality of Tis, T1–2 breast carcinomas: implication for clinical trials of breast-conserving surgery. Cancer 1985; 56:979–990.
31. Lagios MD, Westdahy PR, Rose MR. The concept and implications of multicentricity in breast carcinoma. In: Sommers SG, Rosen PP, eds. Pathology annual. New York, NY: Appleton-Century-Crofts, 1981; 83–102.
32. Schwartz GF, Patchesfsky AS, Feig SA, Shaber GS, Schwartz AB. Multicentricity of nonpalpable breast cancer. Cancer 1980; 45:2913–2916.
33. Rosen PP, Braun DW Jr, Kinne DE. The clinical significance of preinvasive breast carcinoma. Cancer 1980; 46:919–925.
34. Holland R, Connolly JL, Gelman R, et al. The presence of an extensive intraductal component following a limited excision correlates with prominent residual disease in the remainder of the breast. J Clin Oncol 1990; 8:113–118.
35. Tabar L, Fagerberg CJG, Gad A, et al. Reduction in mortality from breast cancer after mass screening with mammography. Lancet 1985; 1:829–832.
36. Baker LH. Breast cancer detection demonstration project: five year summary report. CA 1982; 32:194–225.