Pulse Sequences and Acquisition Techniques for Breast MRI

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Objectives

1. Review basics of MRI breast cancer imaging
2. Present technical challenges of breast MRI
3. Advantages of specialized bi-lateral breast coils
4. Review typical pulse sequences for breast imaging
5. Discuss minimum technical requirements for pulse sequences for ACR accreditation
6. Discuss MRI acquisition protocols, sequence selection and data analysis
7. Present examples of breast MR images
8. Review approaches to image review and analysis

Scientific Foundation of Current Breast MRI Protocols


ACR Breast MRI Accreditation Program
Launched May 2010

Breast Magnetic Resonance Imaging (MRI)
Accreditation Program Requirements

Information available:
www.acr.org
Importance of Both Lesion Enhancement and the Enhancement Pattern


Degree of Enhancement Alone:
- Sensitivity: 91%
- Specificity: 37%
- Accuracy: 58%

Both Enhancement and Curve Type
- Sensitivity: 91%
- Specificity: 83%
- Accuracy: 86%

Group size: 266 cases, 101 cancers

Still not perfect but much better.

Challenges in Dynamic Contrast Enhanced Breast Imaging

1) Enhancing lesions result from Gd contrast agent “leaking” from poorly formed blood vessels within and around the malignant tumor.
2) The contrast agent shortens the T1 of the lesion relative to the surrounding normal tissues and thus may be detected as bright regions on T1-weighted images, provided there is adequate signal-to-noise (SNR).
3) The breast has significant adipose (fatty) tissues, also with short T1, thus create a significant background, fat-suppression is very important.
4) High 3D spatial resolution for small-lesion detection and shape assessment.
5) Enhancement patterns are critical to differentiation of benign and malignant masses, high temporal resolution is essential.
6) Full simultaneous coverage of both breasts is needed for comparison.
7) Image artifacts must be minimized: motion (cardiac and breathing), out-of-volume wrap and non-uniform fat-suppression.

Unfortunately: SNR, spatial resolution, volume coverage and imaging time all compete with one other and artifact free images may be difficult to obtain.

An MR pulse sequence that can meet all of these technical requirements is a significant challenge.

What is the appropriate spatial resolution and SNR?

Basically, the answer is the best you can get and still maintain the necessary SNR and temporal sampling.

The ACR guidelines have stated:
1) < 1.0mm X 1.0mm in-plane pixel size
2) < 3 mm slice thickness (with no slice-gap)
3) “not too grainy”

Comparison: 1.25 X 1.25 mm pixel vs 0.6 X 0.8 pixels
1) Correctly upgraded BI-RADS scores in 13 of 26 cancers
2) Correctly down-graded 10 of 28 benign lesions
How do we fat-suppress the images?

1) Short tau/T1 inversion recovery (STIR)
2) Frequency selective saturation:
   - (FATSat, CHEMSat, CHESS, PRESat)
3) Methods combining frequency selective and inversion recovery:
   - SPIR (Spectral Presaturation with Inversion Recovery)
   - SPAIR (Spectral Adiabatic Inversion Recovery)
4) Phase-cycling:
   - (Dixon method, in-phase/out-of-phase using selected gradient-echo echo times)
5) Highly water-selective binomial RF excitation (e.g. 1-3-3-1)
   - RODEO* (Rotating Delivery of Excitation Off Resonance)

Frequency Selective Fat Suppression

1) Pre-pulse centered at fat resonant frequency with RF-pulse bandwidth set for appropriate volume coverage
2) Nominal fat frequency located at 3.5 ppm below water frequency
3) Important to have homogeneous B0 field
4) B0 field will be affected by magnetic susceptibility of patient: Importance of good auto-shimming.

Frequency-Selective Fat Suppression Pre-pulse

1) A 90° pulse centered at the fat frequency re-orientates the fat protons into the transverse plane, in phase. The spoiling gradients are then used to destroy (crush or scramble) the coherence of the transverse magnetization to ensure that fat does not contribute to the image or
2) a SPAIR pre-pulse that is a 180° inverting pulse followed by a spoiler gradient.

Inversion Recovery (IR) Method

Uses null-point ($M_z = 0$) of T1 recovery
(Occurs at ~ 69% of tissue T1)

Far at 1.5T: $T1 = 250$ msec
Inversion time: $T1 = 160-170$ msec

<table>
<thead>
<tr>
<th>T1</th>
<th>T2</th>
<th>Fat</th>
<th>White Matter</th>
<th>CSF</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>60</td>
<td>700</td>
<td>75</td>
<td>2000</td>
</tr>
</tbody>
</table>

For: $1.5T = (64 \times 10^6 \text{ Hz}) \times 3.5 \text{ ppm} / 10^6 = 220$ Hz
For: $3T = 440$ Hz
What determines adequate temporal sampling?

Enhancement Pattern for Focal Invasive Cancers (Type III Enhancement Curve)

- Time-to-peak enhancement ~ 1-3 minutes

Adequate Temporal Sampling is Essential for Correct Enhancement Curve Classification

- Temporal Sampling rate of >2 minutes (marginal for confident classification)
- Temporal Sampling rate of 1 minute (accurate curve classification)

Gadolinium Contrast Agent: Rate and Volume

1) For accurate timing and consistency, power injector preferred
2) 0.1 mmol/Kg (typically, 10-20 ml volume)
3) Rate ~ 2 ml/s, w/saline flush

3D Fat-suppressed T1-weighted Gradient Echo Sequences

(Most 3D sequences will use centric k-space filling.)

- General Electric: VIBRANT (Volume Image Breast Assessment)
- Philips: THRIVE (T1 High-Res Isotropic Vol Excitation)
- Siemens: VIEWS (fl3d, 3D-FLASH)
- Aurora: RODEO (1993, Harms and Flamig)
- Hitachi: TIGRE
- Toshiba: RADIANCE

Typical Sequence Timing Parameters for T1-weighting:

- TE/TR/\phi: 1-3 ms/4-6 ms/10°-15°
- Acquisition time: 1-3 minutes
Accurate temporal sampling requires specific knowledge of the 3D pulse sequence being used.

1) Time of 3D gradient-echo volume acquisition (16-channel coil)
2) Method of k-space (spatial frequency) filling, e.g. sequential or centric.
Note: May need to contact vendor representative for some of this information.

Acquisition time = TR X slice phase matrix X in-plane phase matrix X NSA

(SENSE, SMASH, GRAPPA, ...)

Example: FOV = 250 mm, Matrix = 356 X 512 X 200 (SENSE)
TE/TR/\(\phi\) = 3.2 ms/6.5 ms/10^2
In-plane phase matrix = 356 (0.7mm X 0.7mm)
Slice phase matrix = 200 (1-2 mm)
SPAIR (Spectrally selective Adiabatic IR) Fat-suppression

Acq. Time = 0.0065 sec X 200 X 356 = 83 sec
2.8 (phase) X 2.0 (slice)

How k-space determines image content
Significance: Acquire center of k-space as contrast agent arrives to ensure maximum contrast enhancement.

The center of k-space occurs when the zero-strength phase-encoding gradients are applied. For 3D phase encoding is applied in two directions: slice and in-plane phase.

Sequential k-space acquisition

The center of k-space occurs at middle of scan

Phantom

How do we achieve simultaneous coverage and good SNR?

Small dedicated coils improve SNR by minimizing body noise

Bilateral coils allow simultaneous coverage. Multi-channel (16) receive-only coil arrays allow acceleration of acquisition times.
Benefit of dedicated receive-only breast coil arrays?

1) Dedicated small coils with FOV closely matching the volume of interest have reduced noise relative to large volume coils. Noise is a function of the sensitive volume of the coil. For volume coils the entire FOV is contributing to noise. The limited sensitive volume of the surface coil has less noise and thus increased SNR.

2) Coil arrays allow reduced image acquisition times via parallel imaging. Current bilateral breast coils may have 16+ parallel receive channels allowing undersampling (acceleration) factors as high as 6.

SENSE* acceleration factor = 2 with 8-coil array

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T1-Weighted 3D Fat-Suppressed Gradient-Echo Sequence (sequential, spiral or 3D “elliptical” k-space filling)

DCE pre-contrast Early post-contrast

Non-uniform fat suppression Enhancing lesion

T2 (fat-suppression) Subtraction: post-pre

3D Flash TE/TR/\(\phi\) = 1.6 ms/4.4 ms/15\(^\circ\) Slice thickness (DCE) = 1.0 mm TA = 86 sec FOV = 300X300 mm Matrix = 448 X 448 Pixel size = 0.7 X 0.7 mm

Coil-array sensitive volume must extend into chest wall.

Pre-contrast image Post-contrast image Subtraction image

Enhancing lesion 5 mm lesion
Good Temporal Sampling Essential for Kinetic Curve Characterization


Artifact

Patient Motion

Out-of Volume Wrap-around

Cardiac Motion

Non-uniform fat suppression

Note: this is the correct PE direction to avoid breast overlap.

Review: Features of Breast DCE Protocol

1. T1-sensitive pulse sequences and simultaneous bi-lateral breast coverage (3D Gradient Echo with shortest TE/TR)
2. High signal-to-noise coils (sensitivity)
3. High isotropic spatial resolution (less partial-volume/lesion detectability)
4. Fat suppression (background suppression/image contrast)
5. High temporal resolution (dynamic pattern definition)

Recommended Breast MRI Protocol

(Image acquisition time ~15-20 minutes)

1) Scout Images (~1 minute)
2) Pre-contrast (~5-7 minutes)
   i. T1-weighted no-fat suppression (fat/glandular morphology)
   ii. T2-weighted with fat suppression (bright fluid for cysts)
   iii. High-resolution, 3D T1-weighted fat-suppressed gradient-echo sequence (pre-contrast baseline image of identifying enhancing lesions)
3) Post-contrast (3-5 volume acquisitions ~ 10 minutes)
   Dynamic multi-phase 3D T1-weighted fat-suppressed GE sequence
   (Note: Pre-contrast and post-contrast images must have identical image parameters to allow subtraction.)
4) Analysis
   i. Subtraction of pre-contrast and post-contrast images (identify enhancing lesions)
   ii. Dynamic contrast curve evaluation (enhancement pattern assessment)
   iii. Maximum Intensity Projection (MIP) images of subtracted images (vascular bed assessment)
CAD programs may improve consistency of breast MRI interpretation


CAD program attempt to automatically identify by:
1. Enhancement threshold
2. Persistence of enhancement
3. Initial peak enhancement

Conclusions

Current imaging protocols for breast cancer assessment rely upon dynamic contrast enhanced (DCE) MRI to provide clearly detectable lesion enhancement as well as an accurate characterization of the lesion enhancement pattern.

To meet these clinical requirements, the technical elements for breast MRI are:
1) A dedicated breast-coil array to provide high SNR images and simultaneous coverage of both breasts.
2) Fat-suppressed, T1-weighted 3D multi-phase gradient echo sequences with high in-plane spatial resolution (< 1mm X 1mm), thin slices (< 3mm) and good temporal resolution (~ 60sec) made possible by using parallel imaging.
3) Post-processing capability should provide post-contrast injection subtraction images, multi-phase time-intensity curves and maximum intensity projection (MIP) for 3D viewing and vascular maps.
**Future:** Kinetic Modeling for estimating Tumor extravasation rate constant: $K_{\text{trans}}$
Extravascular-extracellular volume fraction: $V_e$

DCE kinetic modeling for assessing breast cancer therapy response.

Shift in $K_{\text{trans}}$ Distribution Following Therapy

Pre-therapy
6-weeks of chemotherapy