## Pulse Sequences and Acquisition Techniques for Breast MRI

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## ACR Breast MRI Accreditation Program Launched May 2010

**Breast Magnetic Resonance Imaging (MRI) Accreditation Program Requirements**

ACR American College of Radiology

**Information available:**
**www.acr.org**

## 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

Breast Imaging

Christiane Katharina Kuhl, MD
Peter Mielcareck, MD
Sven Klaschik, MD
Claudia Leutner, MD
Eva Wardelmann, MD
Jürgen Gieseke, PhD
Hans H. Schild, MD

**Dynamic Breast MR Imaging: Are Signal Intensity Time Course Data Useful for Differential Diagnosis of Enhancing Lesions?[1]**

**Kuhl, et. al. Radiology 1999; 211: 101-110**

**Dynamic Image Interpretation of MRI of the Breast**
Christiane K. Kuhl, MD* and Hans H. Schild, MD 2000
JOURNAL OF MAGNETIC RESONANCE IMAGING 12:965-974 (2000)

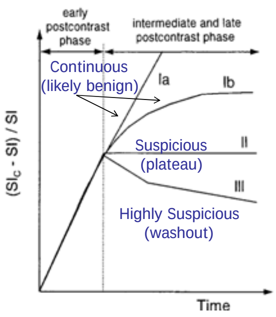
*Radiology*
Christiane K. Kuhl, MD
Hans H. Schild, MD
Nuschin Morakkabati, MD

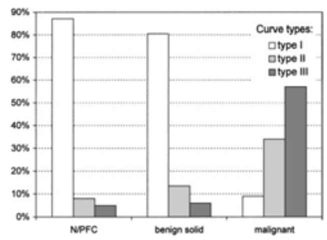
**Dynamic Bilateral Contrast-enhanced MR Imaging of the Breast: Trade-off between Spatial and Temporal Resolution[1]** 2005

**Kinetic Curves of Malignant Lesions Are Not Consistent Across MRI Systems: Need for Improved Standardization of Breast Dynamic Contrast-Enhanced MRI Acquisition**
Sanaz A. Jansen[1]
Akiko Shimauchi
Lindsay Zak
Xiaobing Fan
Abbie M. Wood
Gregory S. Karczmar
Gillian M. Newstead
AJR:193, September 2009 2009

Kuhl, et.al. Radiology 1999; 211:101-110

**Study Group: 266 cases, 101 cancers**

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Importance of Both Lesion Enhancement and the Enhancement Pattern

Kuhl, et.al. Radiology 1999; 211:101-110

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.

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## 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.

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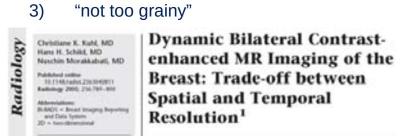
## What is the appropriate spatial resolution and SNR?

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"


Radiology

Christiane K. Kuhl, MD
Hans H. Schild, MD
Naschim Morakkabati, MD

**Dynamic Bilateral Contrast-enhanced MR Imaging of the Breast: Trade-off between Spatial and Temporal Resolution[1]**

Comparison: 1.25 X 1.25 mm pixel vs 0.6 X 0.8 pixels
1) Correctly upgraded BIRADS 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/TI 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)
*Harms,SE, et al Radiology 187: 493-501 (1994)

## Inversion Recovery (IR) Method

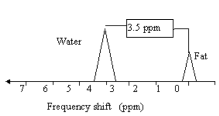
Uses null-point ($M_z$ = 0) of T1 recovery
(Occurs at ~ 69% of tissue T1)

Far at 1.5T: T1 ~ 250 msec
Inversion time: TI ~ 160-170 msec

| (1.5 T) | T1 | T2 |
|---|---|---|
| Fat | 250 | 60 |
| White Matter | 700 | 75 |
| CSF | 2000 | 1000 |

## Frequency Selective Fat Suppression

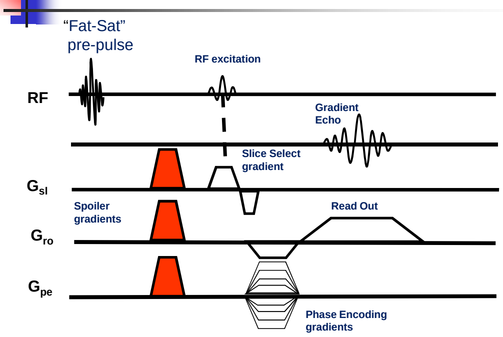
1) Pre-pulse centered at fat resonant frequency with RF-pulse bandwidth set for appropriate volume coverage
2) Nominal fat frequency located at 3.5 ppm below water frequency
3) Important to have homogeneous B0 field
4) B0 field will by affected by magnetic susceptibility of patient: Importance of good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




For: 1.5T = (64 X $10^6$ Hz) X 3.5 pp/$10^6$
~ 220 Hz
For: 3T ~ 440 Hz

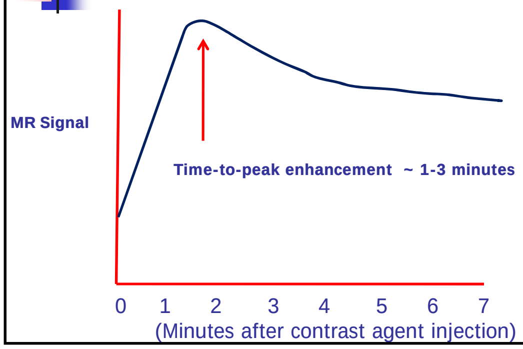
## Frequency-Selective Fat Suppression Pre-pulse

1) A $90^0$ pulse centered at the fat frequency re-orients 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 $180^0$ inverting pulse followed by a spoiler gradient.

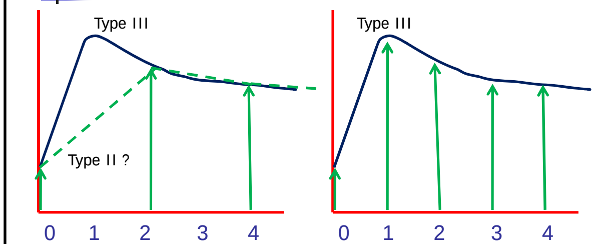


What determines adequate temporal sampling?

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




## 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)

## Gadoliniun 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

MR Compatible Power Injectors

## 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/$10^0$-$15^0$ |
| 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.

Acquistiton time = TR X slice phase matrix X in-plane phase matrix X NSA / Parallel Imaging Undersampling (Acceleration) Factors (SENSE, SMASH, GRAPPA …)

Example: FOV = 250 mm, Matrix = 356 X 512 X 200 (SENSE)
TE/TR/$\phi$ = 3.2 ms/6.5 ms/10$^0$
In-plane phase matrix = 356 (0.7mm X 0.7mm)
Slice phase matrix = 200 (1-2 mm)
SPAIR (Spectrally selective Adiabatic IR) Fat-suppression

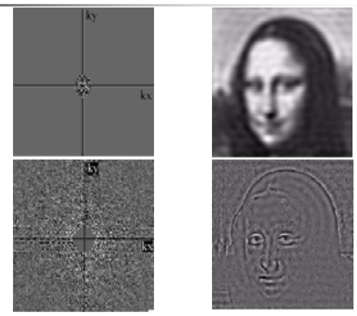
Acq. Time = 0.0065 sec X 200 X 356 / 2.8 (phase) X 2.0 (slice) = 83 sec

## How k-space determines image content

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

Center - contrast

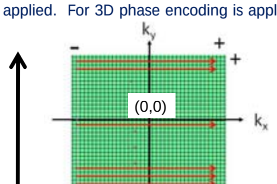
Periphery - resolution

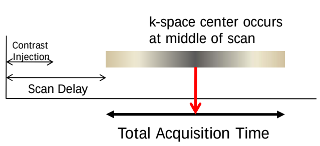



Mezrich R, A Perspective on k-Space: Radiology 1995; 195:297-315

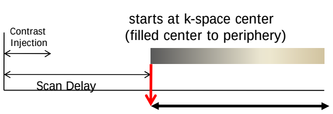
Paschal CB and Morris HD: k-space in the Clinic, JMRI 19(2) 145-159(2004)

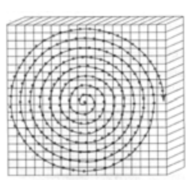
The center of k-space occurs when the zero-strength phase-encoding gradients are applied. For 3D phase encoding is applied in two directions: slice and in-plane phase.



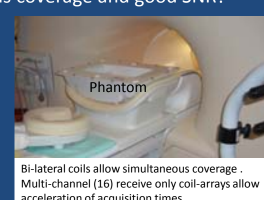

**Sequential k-space acquisition**



**Spiral or centric-elliptical (phase and slice) center-out for 3D k-space acquisition**

## How do we achieve simultaneous coverage and good SNR?

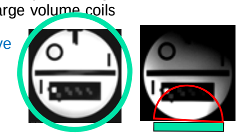





## Benefit of dedicated receive-only breast coil arrays?

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.



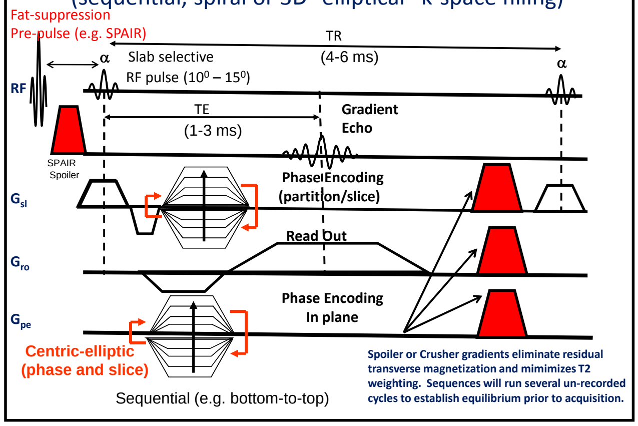
2) Coil arrays allow reduced image acquisition times via parallel imaging

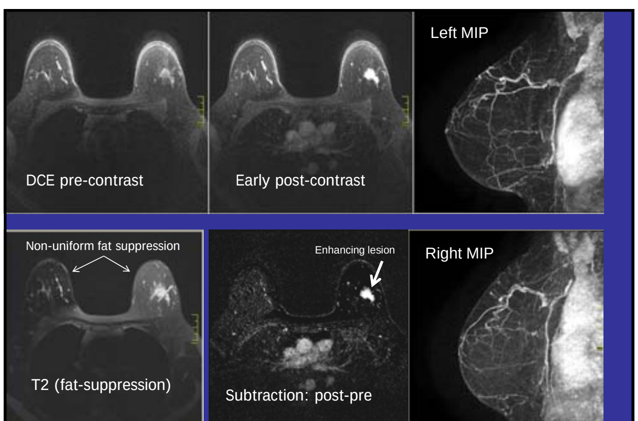
Current bilateral breast coils may have 16+ parallel receive channels allowing undersampling (acceleration) factors as high as 6.

SENSE* acceleration factor = 2 wth 8-coil array

*SENSE Imaging of the Breast, Friedman, et al: AJR (184), pp-448-451 (2005)

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



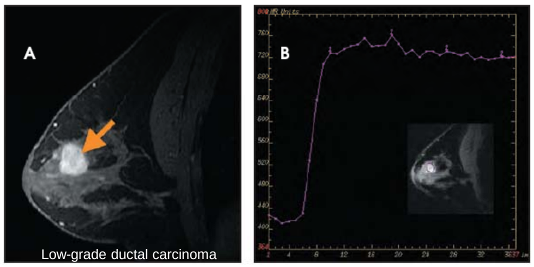




3D Flash TE/TR/$\phi$ = 1.6 ms/4.4 ms/15$^0$ Slice thickness (DCE) = 1.0 mm TA = 86 sec
FOV = 300X300 mm Matrix = 448 X 448 Pixel size = 0.7 X 0.7 mm

## Coil-array sensitive volume must extend into chest wall.


Pre-contrast image | Post-contrast image | Subtraction image

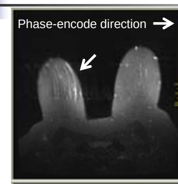
## Good Temporal Sampling Essential for Kinetic Curve Characterization



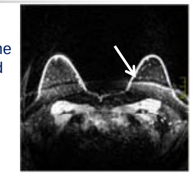

Rakow-Penner R, Hargreaves B, Glover G and Daniel B: Breast MRI at 3T, Applied Radiology pp 6-13, March (2009)

## Artifacts

Patient Motion

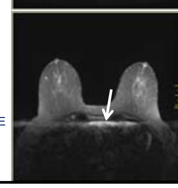



Out-of Volume Wrap-around

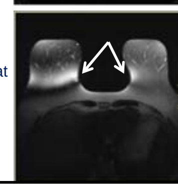


Cardiac Motion

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



Non-uniform fat suppression



## 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 acquisiton 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 paramaters 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)

## ACR Accreditation Pulse Sequence Requirements www.acr.org

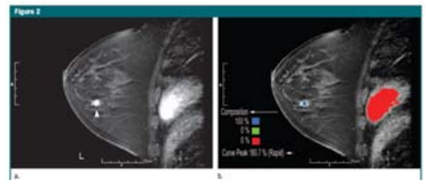
| Sequence | Criteria |
|---|---|
| **T2-Weighted/Bright Fluid Series** | • Adequate SNR/not too grainy<br>• Sufficient bright fluid contrast |
| **Multi-Phase T1-Weighted Series:** | |
| Pre-Contrast T1 | • Adequate SNR/not too grainy |
| Early Phase (first) Post-Contrast T1 | • Adequate SNR/not too grainy<br>• Completed within 4 minutes of completion of injection<br>• Technical factors match pre-contrast T1 |
| Delayed Phase (last) Post-Contrast T1 | • Adequate SNR/not too grainy<br>• Technical factors match pre-contrast T1 |

For the pre-contrast and post-contrast T1-weighted series, the following parameters *must* be met:

| Sequence | Slice Thickness | Gap | Maximum Recommended In Plane Pixel Dimension for Phase and Frequency |
|---|---|---|---|
| Sagittal, Axial and/or Coronal | ≤3 mm | 0 mm | ≤1 mm |

## CAD programs may improve consistency of breast MRI interpretation

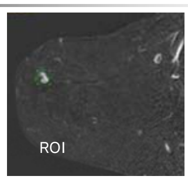
Breast MR Imaging: Computer Aided Evaluation Program for Discriminating Benign from Malignant Lesions,
Williams TC, DeMartini WB, Partridge SC, Peacodk S and Lehman CD, Radiology: Vol 244 (1), pp-84-103 (2007)

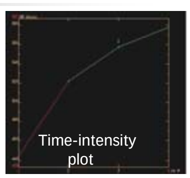


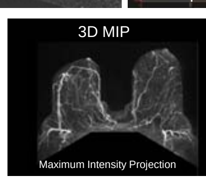

CAD program attempt to automatically identifies lesion by:
1)Enhancement threshold
2)Persistence of enhancement
3)Initial peak enhancement

## Commercial CAD systems are available through MR vendors.

1. Automatic image subtraction
2. ROI time-intensity plot
3. Maximum Intensity Projection (MIP) images
4. Color coded overlay of suspicious enhancement patterns




## 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: $K^{trans}$
Extravascular-extracellular volume fraction: $V_e$

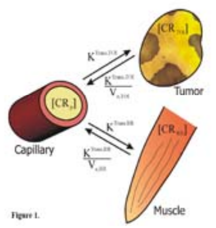


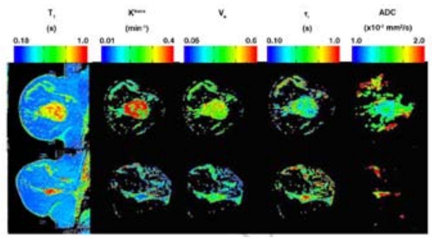

Figure 1.

**Repeatability of a Reference Region Model for Analysis of Murine DCE-MRI Data at 7T**

Thomas E. Yankeelov, PhD, Laura M. DeBusk, MS, D. Dean Billheimer, PhD, Jeffrey J. Luci, PhD, P. Charles Lin, PhD, Ronald R. Price, PhD, and John C. Gore, PhD

JOURNAL OF MAGNETIC RESONANCE IMAGING 24:1140–1147 (2006)

DCE kinetic modeling for assessing breast cancer therapy response.




Integration of quantitative DCE-MRI and ADC mapping to monitor treatment response in human breast cancer: initial results

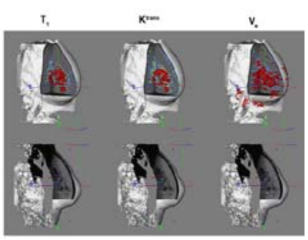
Thomas E. Yankeelov, Martin Lepage, Anuradha Chakravarthy, Elizabeth E. Broome, Kenneth J. Niermann, Mark C. Kelley, Ingrid Meszoely, Ingrid A. Mayer, Cheryl R. Herman, Kevin McManus, Ronald R. Price, John C. Gore

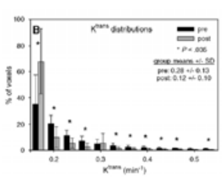
Magnetic Resonance Imaging 25 (2007) 1–13

Shift in $K^{trans}$ Distribution Following Therapy

Pre-therapy

6-weeks of chemotherapy






Magnetic Resonance Imaging 25 (2007) 1–13