Breast MRI: Pulse Sequences, Acquisition Protocols, and Analysis

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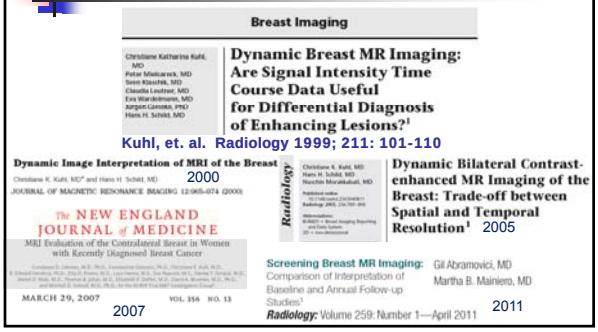
Objectives

1. Review background of MRI breast cancer imaging
2. Present technical challenges of breast MRI
3. Discuss typical pulse sequences
4. Describe typical image acquisition protocols
5. ACR requirements for pulse sequences and protocols
6. Discuss new approaches to image review and analysis

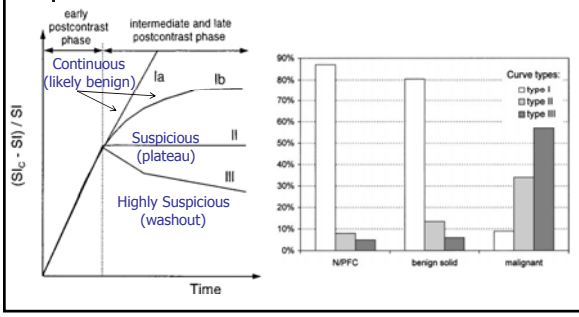
Scientific Background for Current Breast MRI Protocols



Dynamic Contrast Enhanced (DCE) MRI of the Breast

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

Study Group: 266 cases, 101 cancers



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% i.e. high false positive rate
- Accuracy: 58%

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

Group size: 266 cases, 101 cancers

Recent study finds that false-positive rate falls following initial baseline study: 13% to 5.6%

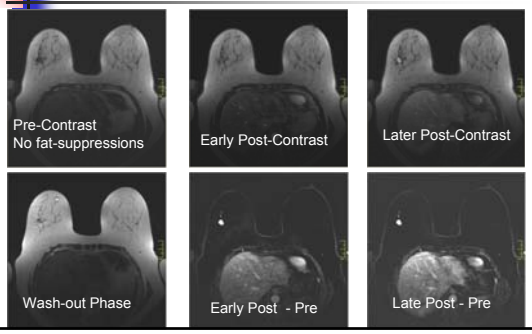
Challenges in DCE Breast Imaging

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 a significant background: ***fat-suppression or subtraction*** is essential.
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 also essential.
6) Full ***simultaneous coverage*** of both breasts: comparison and disease extent
7) Image ***artifacts*** must be minimized: motion (cardiac and breathing), out-of-volume wrap and non-uniform fat-suppression.

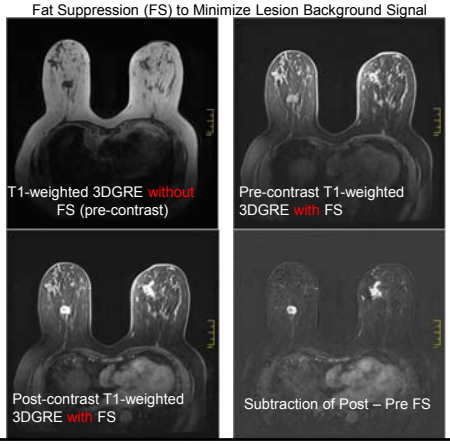
Unfortunately: SNR, spatial resolution, volume coverage and imaging time all compete with one other and artifact free images may be difficult to obtain.

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

DCE T1-weighted images without fat suppression must utilize image subtraction to minimize background.



Fat Suppression (FS) to Minimize Lesion Background Signal



Approaches to Fat Suppression

1) **Short TI inversion recovery (STIR) sequences:**
(Acquire at null-point of fat T1 recovery, $M_z = 0$)

2) **Sequences with frequency selective pre-pulses:**
(FATSat, CHEMSat, CHESS, PRESat)

3) **Combined frequency selective and inversion recovery:**
SPIR (Spectral Presaturation with Inversion Recovery)
SPAIR (Spectral Adiabatic Inversion Recovery)

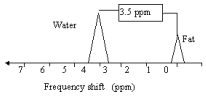
4) **Phase-cycling: 3.5 ppm difference in precessional frequency**
(Dixon method, in-phase/out-of-phase of fat and water signal using selected echo times in gradient-echo sequences.)

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)

6) **Subtraction of pre-contrast images from post-contrast images**

Frequency Selective Fat Suppression

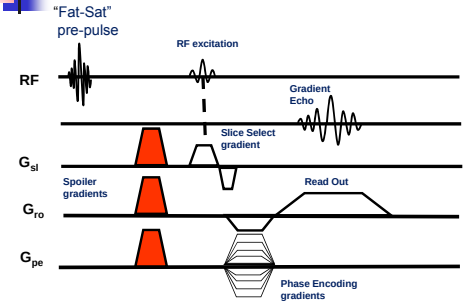
1) Sequence "pre-pulse" at resonant frequency of fat with pulse bandwidth set for appropriate volume coverage
2) Nominal fat frequency located at 3.5 ppm below water frequency
3) Important to have homogeneous B_0 field
4) B_0 field will by affected by magnetic susceptibility of patient: Importance of 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 signal or
2) a SPAIR pre-pulse that is a 180^0 inverting pulse followed by a spoiler gradient.



What spatial resolution and SNR is required?

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

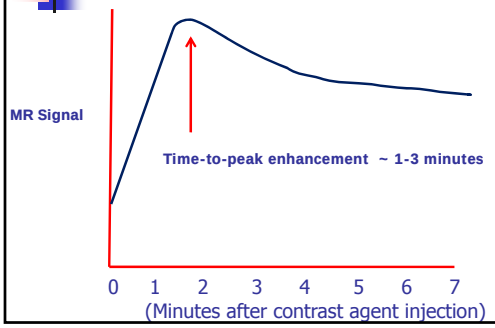
ACR established guidelines:
1) < 1.0mm X 1.0mm in-plane pixel size
2) < 3 mm slice thickness (with no slice-gap)
3) "not too grainy"

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

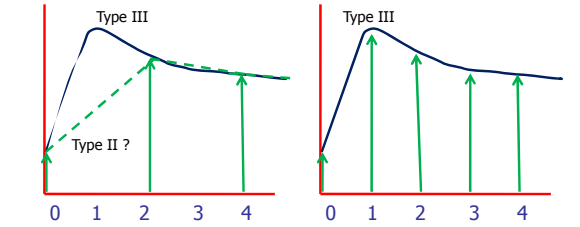
Comparison: 1.25 X 1.25 mm pixel vs 0.6 X 0.8 pixels
1) Correctly upgraded BIRADS scores in 13 of 26 cancers
2) Correctly down-graded 10 of 28 benign lesions

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 (may be 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

Rapid temporal sampling with 3D pulse sequences may require parallel imaging with multi-element coils.

Example of image acquisiton time with a bi-lateral 16-channel coil with parallel-imaging acceleration factor of 5.6.

Note: May need to contact vendor representative for some of this information.

Acquistiton time = $\frac{\text{TR X slice phase matrix X in-plane phase matrix X NSA}}{\text{Parallel Imaging Undersampling (Acceleration) Factors}}$

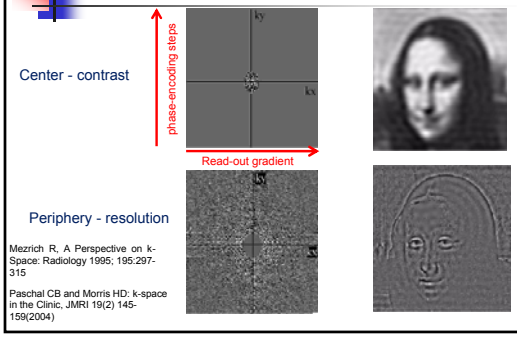
(SENSE, SMASH, GRAPPA ...)

Example: FOV = 250 mm, Matrix = 356 X 356 X 200 (SENSE)
TE/TR/ϕ = 3.2 ms/6.5 ms/10^0
In-plane phase matrix = 356 (0.7mm X 0.7mm)
Slice phase matrix = 200 (1.25 mm slice thickness)
SPAIR (Spectrally selective Adiabatic IR) Fat-suppression

Acq. Time = $\frac{0.0065 \text{ sec X } 200 \text{ X } 356}{2.8 \text{ (phase) X } 2.0 \text{ (slice)}}$ = 83 sec

Image contrast is determined by when the center of k-space is acquired, one k_y step each TR interval.

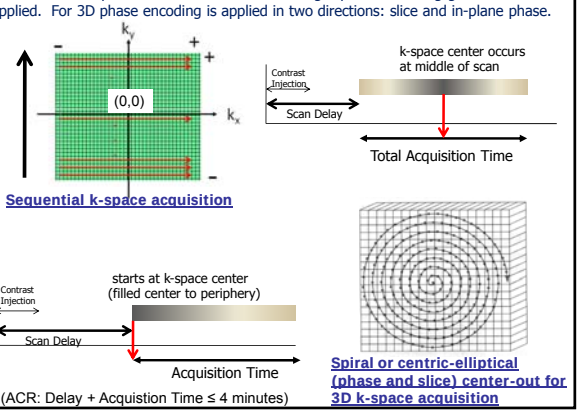
Thus, the center of k-space (k_y=0, k_x=0) should be timed to coincide with the arrival of the Gd contrast agent.



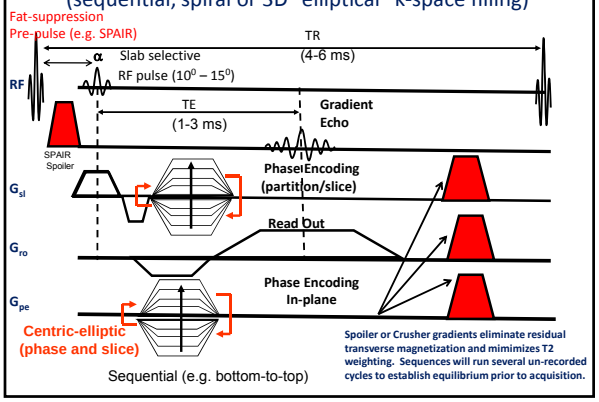
Mezrich R, A Perspective on k-Space: Radiology 1995; 195:297-315

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

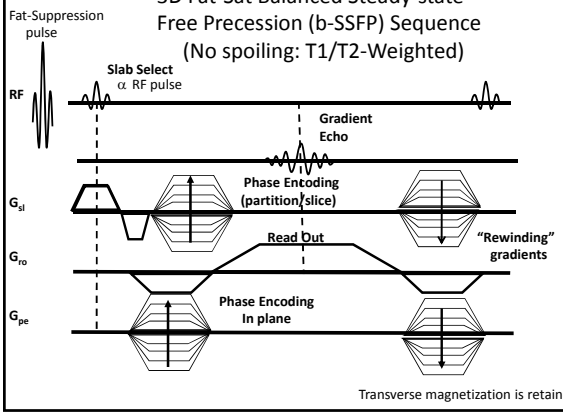
The center of k-space occurs when the zero-strength phase-encoding gradients are applied. For 3D phase encoding is applied in two directions: slice and in-plane phase.



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



3D Fat-Sat Balanced Steady-state Free Precession (b-SSFP) Sequence (No spoiling: T1/T2-Weighted)



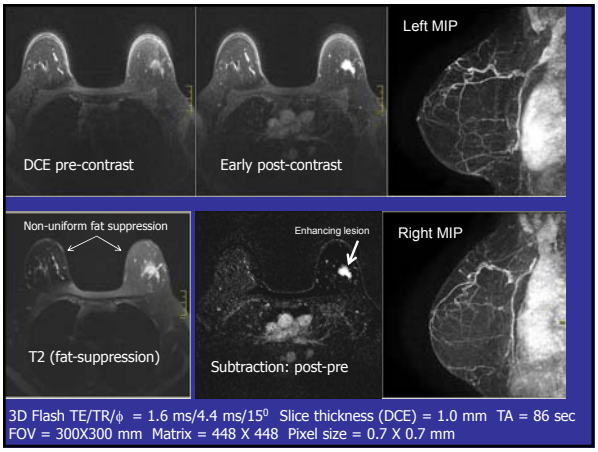
Vendor supplied 3D Fat-suppressed T1-W GE Sequences (Most 3D sequences will use centric k-space filling.)

General Electric	VIBRANT (Volume Image Breast Assessment)
Philips	THRIVE (T1 High-Res Isotropic Vol Excitation)
Siemens	VIEWS (fl3d, 3D-FLASH)
Aurora	RODEO (AuroraEdge, 3DGRE)
Hitachi	TIGRE (fast STIR, FIR)
Toshiba	RADIANCE (FFE_3D2.5_quick)

Typical Sequence Timing Parameters for T1-weighting:

TE/TR/ϕ	1-3 ms/4-6 ms/10^0-15^0
Acquisition time:	1-3 minutes

ACR: ≤ 4 minutes (sum of scan delay and single series time)



Typical 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 Breast MRI Accreditation Program Launched May 2010

Breast Magnetic Resonance Imaging (MRI) Accreditation Program Requirements

ACR American College of Radiology

www.acr.org

ACR Accreditation Pulse Sequence Requirements
www.acr.org

Sequence	Criteria
T2-Weighted/Bright Fluid Series	• Adequate SNR/not too grainy • 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 • Completed within 4 minutes of completion of injection • Technical factors match pre-contrast T1
Delayed Phase (last) Post-Contrast T1	• Adequate SNR/not too grainy • Technical factors match pre-contrast T1

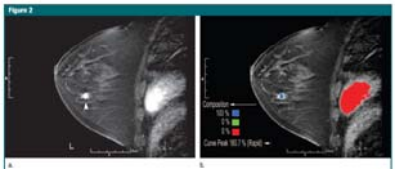
For the pre-contrast and post-contrast T1-weighted series, the following parameters ***must*** be met:

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

Acquisition time ≤ 4 minutes (delay + time to acquire a single image volume)

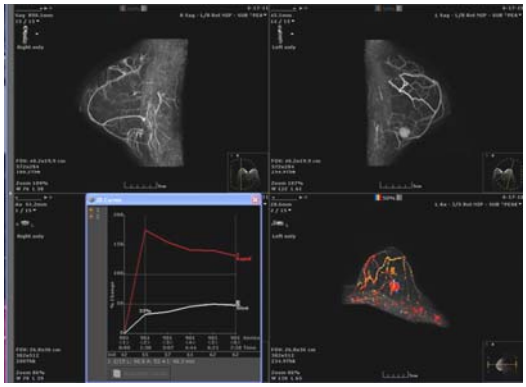
Analysis of DCE images:
CAD programs may improve consistency of breast MRI interpretation

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

Output from comercially available analysis program with automatic color-coding of wash-out curve category.



Future: Kinetic Modeling for estimating
Tumor extravasation rate constant: K^{trans}
Extravascular-extracellular volume fraction: V_e

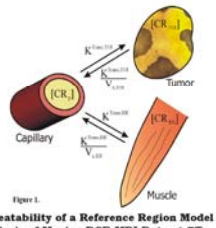


Figure 1.

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

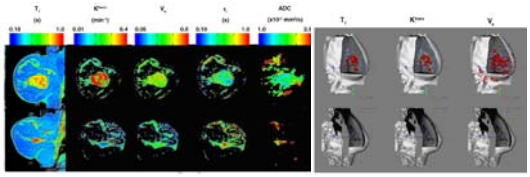
Thomas E. Yankeelov, PhD,[1-4*] Laura M. DeBusk, MS,[5] D. Dean Billheimer, PhD,[6] Jeffrey J. Luci, PhD,[1,2] P. Charles Lin, PhD,[5,7] Ronald R. Price, PhD,[1,5,8,9] and John C. Gore, PhD[1-4]

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

DCE kinetic modeling for assessing breast cancer therapy response.

Pre-therapy

Post-chemo



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

Thomas E. Yankeelov[a,b,c,d,*], Martin Lepage[a,b,e], Anuradha Chakravarthy[f], Elizabeth E. Broome[f], Kenneth J. Niermann[f], Mark C. Kelley[g], Ingrid Meszoely[g], Ingrid A. Mayer[g], Cheryl R. Herman[h], Kevin McManus[h], Ronald R. Price[a,b], John C. Gore[a,b,c,d]

Magnetic Resonance Imaging 25 (2007) 1–13

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 (~ 90sec) 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.

Bi-lateral Multi-channel Breast Coil