Slide 1

Technical Aspects of Quality Control in Magnetic Resonance Imaging

Slide 2

Quality Control of MRI Systems

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Objectives

To gain a general understanding of MR system variability

To be able to set up and manage an MRI QC and Compliance Testing program

To gain a general understanding of MRI Artifacts

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Objectives of an MRI QC Program

- To implement a system practical enough for technologists to utilize on a daily basis
- To obtain meaningful results which reveal system changes before patient care is affected
- To document problems and corrective action in a manner which satisfies accreditation and regulatory requirements

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System Variability

Magnetic resonance imaging systems are subject to variability from:

- Drift in RF Electronics
  - RF Coils
  - RF Transceiver Chain
- Magnetic Field Decay
- Foreign ferro- or para- magnetic material
- Introduction of material producing MRI signal
- Gradient system failures

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Effects of System Variability

Radio Frequency effects

- SNR Loss
  - Occurs when the RF center frequency is off resonance
  - Power is insufficient to produce 90 or 180 deg pulses
  - If the RF coil is detuned
  - If the RF coil homogeneity is not optimized
- Noise
  - Can increase with failures in preamplifier or amplifier
  - Can be introduced with failures in the RF shielding (most often door).

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Gradient effects

- Geometric Distortion
  - Can occur with when maximum amplitude is not achieved or gradient is miscalibrated.
  - Can occur if eddy current compensation changes
- Spatially Dependent SNR Loss
  - Can occur when local field homogeneity decreases
  - Can occur when gradient waveforms are not optimized (eg eddy currents) resulting in incomplete rephasing of echo
- Phase Errors
  - Cause misregistration in Phase Encoding direction
  - Can arise from any of the 3 orthogonal gradients

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Magnetic Field Inhomogeneity

- SNR Loss
  - Can occur when local total field homogeneity decreases $\Rightarrow \downarrow$T2*.
  - Can occur when center frequency is shifted beyond bandwidth of receiver
- In Plane Geometric Distortion
  - Can cause regions of low or high signal when resonant frequency is shifted beyond bandwidth of a pixel

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Magnetic Field Inhomogeneity

- Geometric Distortion in Slice Select Direction
  - Can cause misregistration of signal as a function of slice location, or distortion of slice profile causing increased “crosstalk”.
- Chemical Shift Frequency Offsets
  - Frequency selective pulses (e.g. lipid or water saturation, mtc) can have a spatial dependence to their intended effect.

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Daily Testing

ACR MRI Accreditation Recommendation

- Magnetic Field Stability (Center Frequency)
- Signal to Noise Ratio
- Artifact Inspection

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Standard Pulse Sequences

	T1 Weighted	*T2 Weighted*
TR	500	2000
TE	min full <20msec	20/80 or 30/90
Matrix	128 or 160	128 or 160
Coil	Head	Head
#excitations	1	1
FOV	24or 25	24 or 25

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Magnetic Field Stability
(Center Frequency)

- Test Object
- Procedure
  - Sequence Parameters
  - What to record
- Factors influencing measurement

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Center Frequency (cont.)

Typical magnetic field stability is on the order of 0.1 ppm per hour or 2.4 ppm per day. At 1T this corresponds to approximately 100 Hz decay of the center frequency per day and 150 Hz per day at 1.5 tesla. A graph of center frequency vs. time should indicate steady decay, however, typical inhomogeneity over a 20 cm DSV is also within this range. Therefore, it is important to set up conditions over which reproducible measurements of the center frequency can be obtained.

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Center Frequency (cont.)

Additional magnetic fields due to variation in magnetic susceptibility can distort the line shape of the resultant water signal and produce an error in determining the peak position. This is minimized by using a spherically symmetric uniform phantom.

Measurement of center frequency is further complicated by the presence of additional static magnetic fields used to adjust the homogeneity for specific applications (shims). The shim settings can be modified in two ways.

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Center Frequency (cont.)

Routine preventative maintenance for MRI calls for periodic re-shimming of the magnet using all the available set of shim fields. These shims involve coils designed to vary magnetic field as a function of spatial coordinates. Usually the set of coils includes shims which perturb the magnetic field spanning geometry characterized by second order spherical harmonics. These shim settings are usually not changed by the user.

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Center Frequency (cont.)

Many manufacturers provide user controlled shimming using the three linear gradient magnetic fields, either manually or with a computer controlled algorithm (autoshimming). Some manufacturers utilize autoshimming before each pulse sequence.

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Center Frequency (cont)

Unaccounted shimming can add an additional magnetic field resulting in an increase in the center frequency from day to day. It is important therefore to use the same setting of the shim magnetic field gradients for each measurement.

The graph of center frequency over a period of 15 months shows an increase in center frequency at several time points. The overall decrease in magnetic field is less than 160 Hz << less than manufacturer's specification

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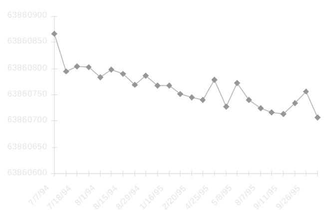
Center Frequency over 15 Month Period



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Center Frequency (cont)

Procedure

- Prescribe a standard T1 weighted single slice pulse sequence
- Make sure any auto shimming algorithm is turned off.
- Set up parameters for the auto pre-scan and load the pre-set values of the shims.
- Perform the clinical auto pre-scan procedure.

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Center Frequency (cont)

Procedure

- Record the time of the measurement, resultant center frequency, and shim file settings.
- Optionally record the transmitter and receiver gains. If the same shim file setting was used subtract the previous days frequency from the current value and compare with the specified decay.
- If the measurements were not acquired at the same time on successive days, adjust for total decay time.
- Action level: decay within manufacturer specification.

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Signal to Noise Ratio

- Test Objects
  - Material
  - Geometry
    - RF Homogeneity
    - Magnetic Susceptibility Effects
  - Positioning
- Coil

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Signal to Noise Ratio

In measuring signal to noise ratio, a uniform test object is necessary in order to minimize loss of signal due to variation in magnetic susceptibility as well as spatial variation in the signal intensity due to RF inhomogeneity.

Solutions which are not comparable to tissue conductivity may not load the coil properly.

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Signal to Noise Ratio (cont.)

The choice of coil is determined by the largest volume of procedures performed clinically, the best homogeneity characteristics, and the ease of both acquiring and analyzing the data. Though in some instances the head coil is not always used for the largest number of procedures, it usually has superior homogeneity compared to surface coils used in spine or extremity imaging.

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Signal to Noise Ratio (cont.)

Example Pulse sequence

- TR - 500 to 800 milliseconds
- TE - 10 to 20 milliseconds
- Single 10mm slice at isocenter.
- Single excitation, 256 x 160 matrix
- FOV - 20 to 24cm.

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Signal to Noise Ratio (cont.)

These parameters are used to generate a T1 weighted image. Specific TR, TE etc., can be taken from a common clinical protocol, provided the T1 of the test object material is within the range of normal tissue. Once chosen, these parameters should be remained fixed as they all affect the resultant signal to noise ratio.

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Signal to Noise Ratio (cont.)

Use of the minimum TE as calculated by the imaging system is not recommended since this value will change with changes to software and hardware.

Test object dimension and FOV should be chosen to fill greater than 85% of the usable field view of the coil in order to adequately take into account RF homogeneity effects.

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Signal to Noise Ratio (cont.)

ACR Accreditation “T1” Series

TR	500
TE	20 msec
Matrix	256
Coil	Head
#excitations	1
FOV	24or 25
Time	2:16

Use of 256 matrix is not necessary for SNR, however, if using the ACR phantom, other tests may be analyzed. The extra minute is small compared to set up time (aligning the phantom).

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Signal to Noise Ratio (cont.)

Noise Characteristics

Theoretically, noise in magnetic resonance is random. In practice however, there can be systematic contributions to background noise arising mainly from unwanted phase shifts acquired in the RF transceiver chain. Since phase is used in the image reconstruction algorithm to supply spatial information, these phase shifts produce spatial variation in this background signal (“ghosts”).

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Signal to Noise Ratio

In measuring signal to noise ratio, a uniform test object is necessary in order to minimize loss of signal due to variation in magnetic susceptibility as well as spatial variation in the signal intensity due to RF inhomogeneity.

Solutions which are not comparable to tissue conductivity may not load the coil properly.

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Analysis

If S is the mean of the ROI from the original image and σ_N is the standard deviation of an ROI from the noise image, then

$$SNR = \sqrt{2}\,\frac{S}{\sigma_N}$$

Record the SNR along with means and standard deviations.

Action level: SNR within manufacturer specification

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Signal to Noise Ratio (cont.)

Noise Estimation: Method 1

While it may be attractive to measure the noise of a region of interest from a non signal producing area of the image field of view outside the test object using a single image, this practice may introduce systematic noise into the calculation of the SNR. If a single acquisition is desired, estimate noise from multiple regions in the image.

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Signal to Noise Ratio (cont.)

Procedure

1. Scan test object once using T1 series.
2. Choose ROI that encompasses at least 75% of the test object. Measure and record mean and standard deviation of the ROI
3. Calculate PSG from ACR accreditation.
4. If PSG acceptable, use average of 4 ROI σ's to estimate noise.

Benefit is that PSG measurement can be tracked

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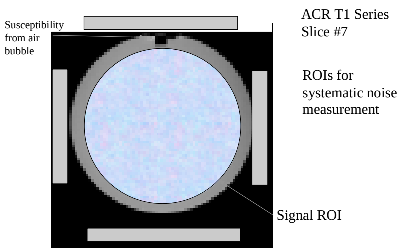
Signal to Noise Ratio (cont.)



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Signal to Noise Ratio (cont.)

SNR and PSG for three systems

	Fixed 11.5T		Fixed 2 1.5T		Mobile 1.0 T	
	Mean	σ	Mean	σ	Mean	σ
L	12.08	5.82	11.22	5.87	20.96	11.77
R	11.18	6.87	10.59	6.15	22.59	10.40
T	10.42	5.13	9.93	5.07	20.28	10.18
B	9.04	4.41	10.47	5.14	19.14	10.04
Signal	1168.00	50.35	1407.19	40.32	1451.46	50.00
Noise Ave	10.68	5.56	10.55	5.56	20.74	10.60
PSG	0.001627		0.000501		0.001423	
SNR	297.2202		358.0868		193.6942	

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Signal to Noise Ratio (cont.)

Noise Estimation: Method 2

An accepted practice is to image the test object twice, repeating the acquisition within a few minutes of the first. The noise is estimated from an ROI in an image formed by subtracting the first acquisition from the second. The assumption is that the signal (and noise) in the two images are uncorrelated.

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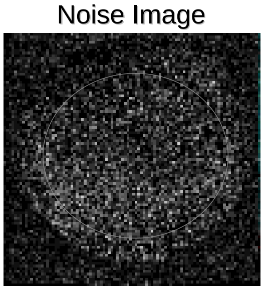
Noise Image



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Signal to Noise Ratio (cont.)

Procedure

1. Scan test object twice using same parameters.
2. Subtract the second image from the first on a pixel by pixel basis. (This may require the images to be downloaded to a work station).
3. Choose ROI that encompasses at least 75% of the test object. Measure and record mean and standard deviation of the ROI in both the original images and the subtracted noise image.

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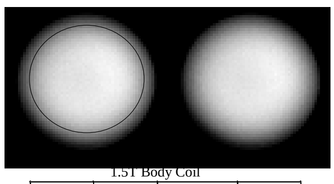
SNR Method 2



1.5T Body Coil

Plane	S	σ	SNR
Axial	1185	11.5	145.7255
Sagittal	1184	11.62	144.0989
Coronal	1174	11.5	144.3728

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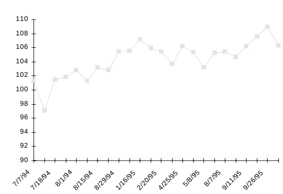
SNR over an 15 Month Period



A graph of SNR in the head coil over 15 months show day to day variation of SNR with a mean =104.3 and σ=2.6

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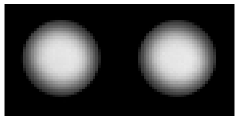
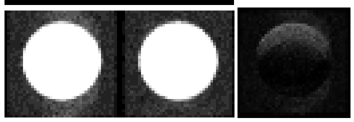
Systematic Background



Axial
Body Coil
FOV 36 cm



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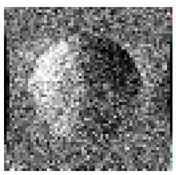
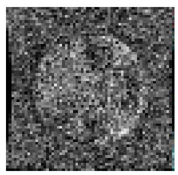
Systematic Background

Sagittal



Coronal



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Weekly Testing

- ACR
  - Processor sensitometry
- Other
  - Phase Stability
  - Magnetic Field Homogeneity
  - Signal - to - Noise Ratio in orthogonal planes
  - Image Uniformity

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Processor Sensitometry

Though analogous to other digital imaging modalities, printing of MR films can be problematic due to variation in the output of the MR system. This variation is due to

- Variable gain in the transceiver subsystem
- Variation in tissue contrast (T1, T2,)
- Variation in operator selectable parameters

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Processor Sensitometry

Example Protocol

- Display SMPTE pattern
- Inspect SMPTE image on the monitor
  - **Note 5% and 95% levels visibility**
  - **Note any artifacts**
- Film image using preset window and level
  - Window width 256, Window level 128
- Scan output image and record
  - Speed, Contrast, Base+Fog

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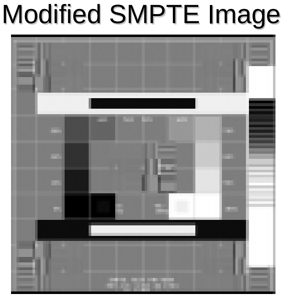
Modified SMPTE Image



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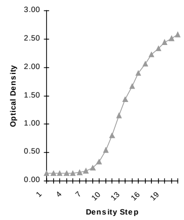
Tone Scale Calibration



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Processor Sensitometry

This procedure allows a standardized way of comparing the image on the monitor with the output of the laser printer. The film densities may be scanned, plotted, and interpreted in a manner consistent with other processors used in the department, however, this test does not narrow the source of a potential problem to either the monitor, MRI console output (either video or digital), laser printer performance, or processor performance.

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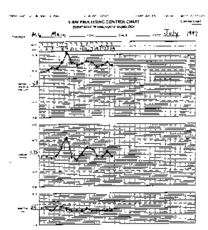
Processor QC



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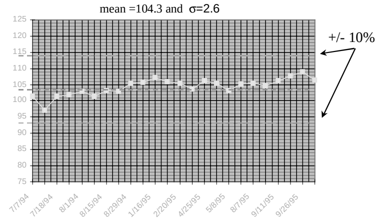
SNR Results

mean =104.3 and σ=2.6



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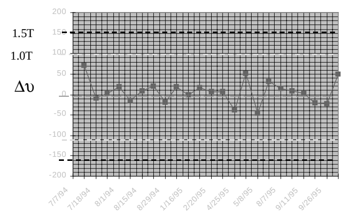
Daily Change in Frequency



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Review of Test Results

- Technologist - Daily Checklist
  - Inspect QC phantom for artifacts
  - Inspect SMPTE Pattern for artifacts (monitor)
  - Inspect SMPTE Pattern for artifacts (film)
  - Graph Center Frequency, SNR, Sensitometry
- Physicist
  - Review of Daily QC
    - Monthly or Quarterly (ACR Semi-Annual)
  - Review Artifacts, Action Limits -ad hoc

Slide 1

Artifact Inspection

MRI is susceptible to artifacts:

- Low SNR (and low energy) compared to other imaging modalities
- Ability to directly modify spatial frequency sampling
- Sensitivity to metallic objects
- Patient – RF coil interaction is variable

Slide 2

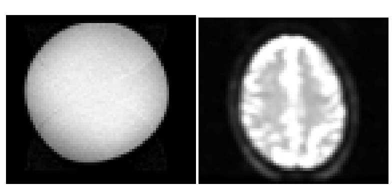
Artifact Inspection

Artifacts may appear differently in test objects and patients because of differences in:

- Magnetic susceptibility
- Coil loading
- T1, T2 of test object material
- High contrast between plastic (no signal) and fluid

Slide 3

EPI 1/2 FOV Phase Artifact



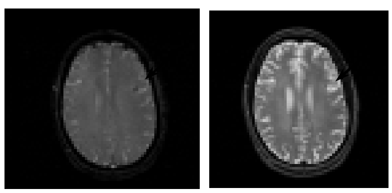
Slide 4

Artifact Inspection

A single source may cause artifacts to appear differently
- Using different coils
- Using different pulse sequence parameters
  - Anatomic plane
  - pulse sequence type (eg spin echo vs. gradient echo)
  - timing (TR, TE, gating)
  - Spatial resolution (FOV, matrix size)
- Using different materials

Slide 5

Gradient Echo vs. SE of Bleed



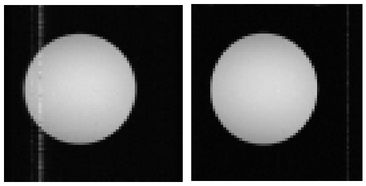
Slide 6

RF Artifacts

External RF Noise
- Specific frequency usually one pixel in width
- Phase Incoherent
- Independent of anatomic plane
- May change position with FOV or bandwidth

Slide 7

External RF Noise



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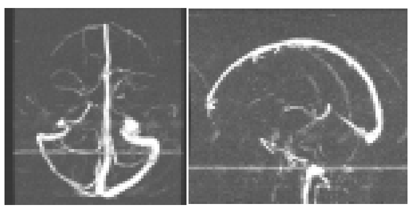
External RF Noise



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RF Artifacts

- Transmit Receive switch failure
  - Inductive coupling of transmit coil and surface coil
  - Spatial variation in RF power

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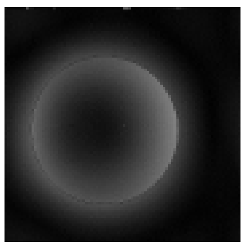
Transmit - Surface Coil Artifact

Array

Slide 11

ADC Overflow (Clipping)



Occurs when the signal is larger than the maximum ADC value, usually if gain is set too high.

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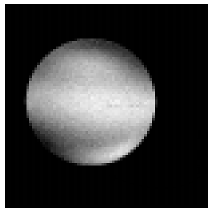
Non Phase Encoded Signal

- Stimulated Echoes
- FID (inhomogeneous B1, gradients)
- Signal from outside FOV
  - Usually if phase and frequency directions swapped.
  - Small FOV in larger body part

Slide 13

Stimulated Echo Interference



inge spacing inversely
oportional to difference
echo timing.

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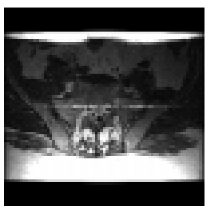
Axial, Sagittal Lumbar Spine



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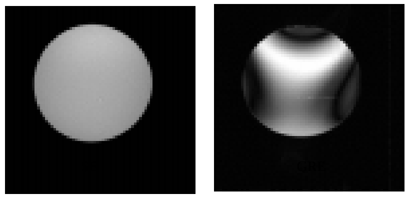
Homogeneity Artifacts

- Local inhomogeneity
  - causes shifts in position in frequency encoding direction
  - causes dephasing within a voxel
  - causes frequency selective pulses to be spatially shifted
- Generally independent of pulse sequence parameters except
  - worse on gradient echo vs spin echo
  - saturation pulses

Slide 16

Homogeneity Artifacts

Shim Misadjusted



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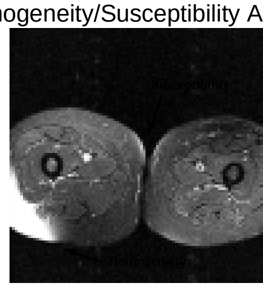
Homogeneity/Susceptibility Artifact



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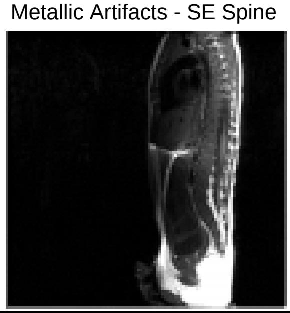
Metallic Artifacts - SE Spine



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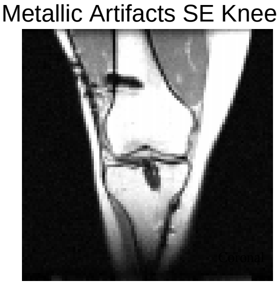
Metallic Artifacts - FSE Spine

Slide 20

Metallic Artifacts - SE Spine

Slide 21

Metallic Artifacts SE Knee



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Metallic Artifacts FSE Knee

onal
Sat

Slide 23

Metallic Artifacts FSE Knee

Sagittal
Fat Sat

Slide 24

Gradient Artifacts

- Geometric Distortion
  - Similar to Metallic Artifact but usually over FOV
- Direction Dependent
  - In plane Frequency vs. Phase
  - Slice profile distortion

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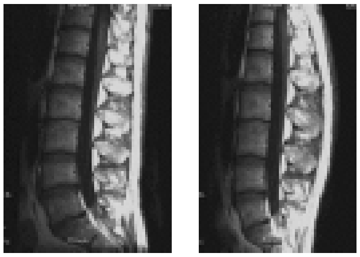
Geometric Distortion



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Phase Artifacts

- Gradient effects
  - Spatially dependent SNR loss
  - Ghosts
    - Differentiate from motion
- Non gradient effects
  - Phase Modulation Ghosts
  - DC offset

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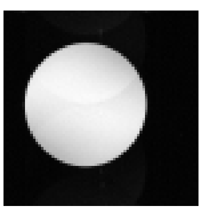
Phase Modulation Artifact



- Weak Ghost displaced in PE direction
- Periodicity dependent upon synchronization with TR
- Line voltage, harmonics
- Gradient instability

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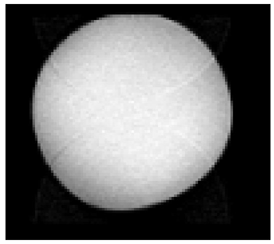
EPI 1/2 FOV Phase Artifact



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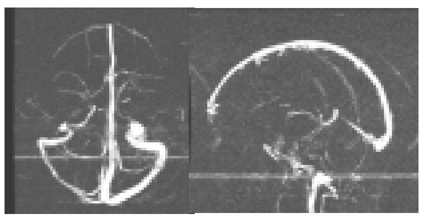
Phase Contrast Venogram



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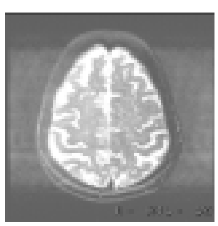
Gradient Instability Artifact



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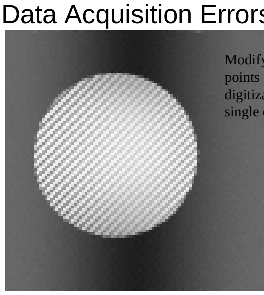
Data Acquisition Errors

- Data corrupted during digitization before FFT (eg electrical transient)
- Bad memory locations
- Pattern depends on what data points are modified

Slide 32

Data Acquisition Errors



Modifying a few points during digitization of a single echo.

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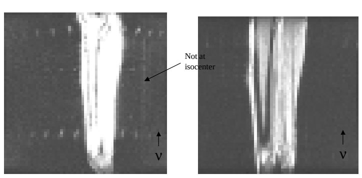
Signal Corrupted During Scan

Similar to a data acquisition error, the signal may be modified by discrete events during any part of the pulse sequence. Their effect upon the image depends upon when and how many events occur.



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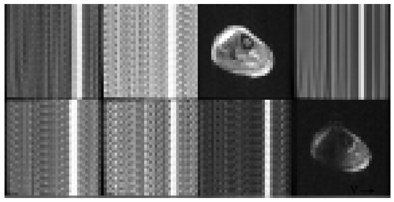
Signal Corrupted During Scan



Noise appears to be phase incoherent at specific frequencies on upper right.

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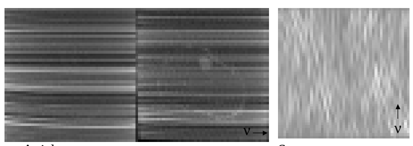
Signal Corrupted During Scan



Axial Sag

High frequency or high contrast residual image of leg
Two dimensional pattern

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Artifact Summary

- Artifact vary with imaging conditions
  - Pulse sequence details, coil, patient
- RF Artifacts
  - External noise phase incoherent, single pixel
  - Other artifacts not along orthogonal directions
  - Phase modulation - ghosts in PE direction
- Gradient Artifacts
  - Instabilities - Ghosts in PE direction
  - Distortion - direction dependent
  - Severity, appearance direction dependent

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Acknowledgments

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http://bmrl.med.uiuc.edu:8080/~cgregory/notebook/artifacts.html