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MR Acceptance Testing and Quality Control:

Report of AAPM MR Subcommittee TG1

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THE UNIVERSITY OF TEXAS MD ANDERSON CANCER CENTER *Making Cancer History*™

Learning Objectives

1. Understand the requirements for MR site and system acceptance tests.
2. Review recommended MR site and system acceptance testing procedures, including phantom selection, data acquisition, data analysis, and reporting.
3. Review recommended action criteria for both standard imaging options and advanced imaging and spectroscopy options.

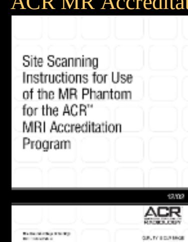
Previous MR Committee TG Reports

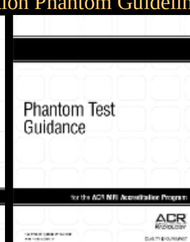
Previous AAPM MRI acceptance testing and QA guidelines:

- *Acceptance Testing of Magnetic Resonance Imaging Systems: Report of AAPM Nuclear Magnetic Resonance Task Group No. 6* Och, Clarke, Sobol, Rosen, Mun. *Med Phys* 19(1):217-229, 1992.
- *Quality Assurance Methods and Phantoms for Magnetic Resonance Imaging* Price, Axel, Morgan, Newman, Perman, Schneiders, Selikson, Wood, Thomas. Report of Task Group No. 1, AAPM Nuclear Magnetic Resonance Committee, *Med Phys* 17(2):287-295, 1990.

ACR Testing Guidelines

ACR MR Accreditation Phantom Guidelines:





These documents are available from the ACR (www.acr.org)

Levels of Involvement

- Naturally, it is preferable to have involvement at each of the following stages:
  - System specification (scanner type, options, *etc.*)
  - System siting (construction, remodeling, interference from/with surrounding equipment)
  - Site testing (shielding)
  - System testing
- Practically, this seldom happens!

MR Acceptance Test Reality Check

- What can I test independently? What tests can I accomplish using the vendor's service tools and/or reports?
- For independent testing, what tools (hardware *and* software) are necessary? Do I have them? If not, is it worth acquiring or developing them?
- I have *at least* 5 major pulse sequence classes, 3 principal planes (not including obliques), and 10 or more RF coils. Just how much do (can) I test?
- What are the unique applications of the MR systems at the particular site?

Outline

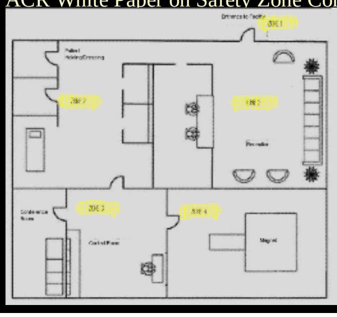
- Siting tests
- General system checks
- Phantoms for acceptance testing
- Magnet subsystem tests
- RF subsystem tests
- Gradient subsystem tests
- Combined RF/Gradient tests
- Global system tests
- Testing of optional capabilities, *e.g.*, EPI and MRS

MR Siting Issues

- MR facilities are, in several specific ways, unique with respect to site planning, construction, and commissioning.
- Each of the following issues should be considered:
  - MR safety issues and access control
  - Vibration
  - Floor loading and access for equipment delivery
  - Magnetic field shielding
  - RF shielding
  - Cryogen exhaust and other emergency systems
  - Reuse of MR scan room for other uses

MR Site Safety Issues / Access Control

ACR White Paper on Safety Zone Concept



- Zone 1
  - Open access
- Zone 2
  - Preparation and holding
- Zone 3
  - Carefully controlled by MR facility personnel. May be partially within 5 G exclusion zone.
- Zone 4
  - Actual scan room. No admittance w/o documented training and screening.

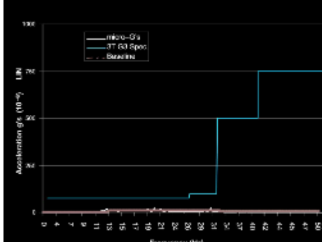
MR Siting Issues – Weight, Dimensions

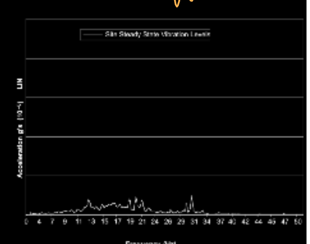
- Weight loading
  - The weight of the magnet subsystem varies dramatically depending on design.
    - Permanent magnets: ~ 40,000 – 50,000 lbs
    - Active shield 1.5T: ~ 12,000 – 15,000 lbs
    - Active shield 3.0T: ~ 22,000 – 26,000 lbs
  - Floors (at least below the magnet) have fiber reinforced concrete; no rebar.
- Typical magnet delivery hatch / wall opening: 8-9' x 8-9'
- Typical minimum scan room dimensions: 11-13' x 18-20'

Siting - Vibration

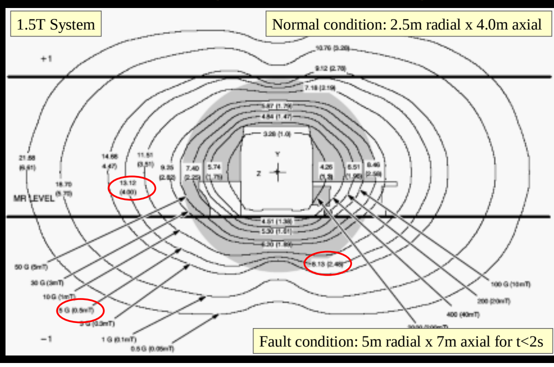
- Excessive vibration levels will result in image artifacts (ghosting in the phase-encoding direction).
- Most MR system vendors specify acceptable transient and steady-state vibration levels (as a function of frequency).
- With modern magnets that are smaller and lighter, vibration is more of an issue than it was previously.
- Before system installation it is recommended to have an acoustical engineering contractor perform transient and steady-state vibration measurements.

Siting - Vibration

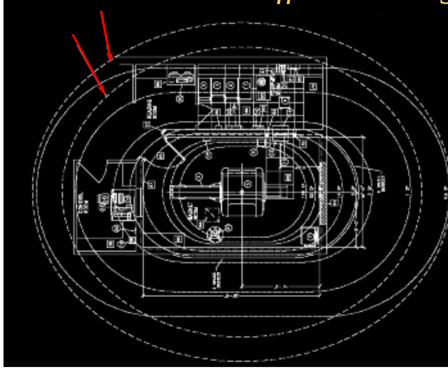




MR Siting Issues – Fringe Fields



The Site Can Affect the Magnet, Too!



"Moving Metal Sensitivity Lines"

Large, moving ferrous objects can transiently affect magnetic field homogeneity.

When is Magnetic Shielding Required?

- To constrain 5G lines, if necessary.
- To minimize effects of the magnet on equipment in adjacent rooms, particularly those devices that require highly accurate focusing of drifting charged particles!
- Some MR vendors provide proximity charts that give guidelines for various types of equipment.

Example Proximity Chart

0.5 GAUSS (0.05mT) OR LESS	• Nuclear cameras	
1 GAUSS (0.1mT) OR LESS	• Positron Emission Tomography scanner • Linear Accelerator • Cyclotrons • Accurate Measuring scale • Image intensifiers • Color TV	• Video display (color, B/W, monochrome) • CT scanner • Ultrasound • Lithotriptor • Electron microscope • Advantage Workstation with CRT Monitor
3 GAUSS (0.3mT) OR LESS	• Power transformers • Main electrical distribution transformers • Moving steel equipment such as: – Vehicular traffic – Fork lift trucks – Dumb waiters – Electric transport carts	– Loading dock (truck traffic) – Elevators – Escalators – Helicopters (See Note 3)
5 GAUSS (0.5mT) OR LESS	• Cardiac pacemakers • Neurostimulators	• Biostimulation devices

Example Proximity Chart (cont.)

10 GAUSS (1mT) OR LESS	• Magnetic tapes and floppy discs • Hard copy imagers • Line printers • Video Cassette Recorder (VCR) • Film processor • Credit cards, watches, and clocks • Telephone switching station • Water cooling equipment • HVAC equipment	• Major mechanical equipment room • Large steel equipment such as: – Emergency generators – Commercial laundry equipment – Food preparation area – Air conditioning chiller – Fuel storage tanks – Motors greater than 5 horsepower • X–ray tubes
30 GAUSS (3mT) OR LESS	• RFS Cabinet • Twin Accessory Cabinet (TAC) • 32 Channel Cabinet (Option)	• MRCC equipment • GWHX equipment • Chilled Air blower (CAB) for IPCM Option
50 GAUSS (5mT) OR LESS	• GOC Computer Cabinet • LCD Color Monitor for OW (See note 5) • NB RF Amp Cabinet • HFD/PDU Cabinet • Main Disconnect Panel • Magnet Monitor • Telephones	• Metal detector for screening • LCD Color Monitor for Advantage Workstation • Broadband (BB) RF Amplifier Cabinet for 8KW MNS (Option) • BrainWave HW Lite Cabinet (Option) • CAB–MDP for IPCM Option
100 GAUSS (10mT) OR LESS	• Shield/Cryo Cooler Compressor Cabinet • Service Tool Magnet Power Supply Cabinet • Service Tool Shim Power Supply Cabinet	• Pneumatic Patient Alert Control Box • Oxygen Monitor (Option)
200 GAUSS (20mT) OR LESS	• Penetration Panel • Blower Box	• Magnet Rundown Unit • Remote Oxygen Sensor Module

Siting - Magnetic Field Shielding

Magnetic Shielding Techniques

– None

5 G line at ~11 m from isocenter for 1.5T

– Passive Shielding - high permeability metal surrounding magnet and/or in surrounding walls.

5 G line at ~5.8 m from isocenter for 1.5T

– Active Shielding - second set of supercon coils designed to greatly attenuate B_0 field outside of magnet.

5 G line at ~4 m from isocenter for 1.5T

– Active/Passive Shielding

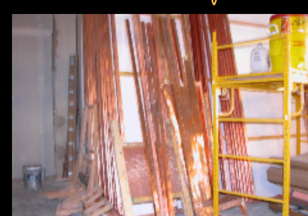
Siting - Magnetic Field Shielding

- Fringe fields should be measured with handheld gaussmeter and mapped onto site drawings.
- 5 G lines should be posted using appropriate signage (multilingual as needed). Any persons with cardiac pacemakers or neurostimulators should not enter the 5 G exclusion zone.
- Map fringe fields in patient waiting areas, restrooms, patient corridors, *etc.* as well as technical areas, particularly at the scan console.

(1.5T scanner: ~14G [unshielded], ~1G [shielded])

Siting - RF Shielding

Silica Steel Mag Shielding and Copper RF Floor Shielding



Copper RF Shield Panels

Siting - RF Shielding

RF Shield Near Completion

Penetration Panel, Filters, Waveguides

Siting - RF Shielding

- Amplitudes of the detected signals are in the micro- or millivolt range.
- Therefore, MR scanners are contained in a Faraday cage constructed of copper or aluminum to eliminate ambient RF noise from outside the room.
- Typical RF shield specifications:
  - $\leq$ 1.5T: $\geq$ 100 dB attenuation of 100 MHz planewave
  - 3.0T: $\geq$ 100 dB attenuation of 150-170 MHz planewave
  - At least 1 kΩ ground isolation
- RF signal generator, amplifier, transmission and reception antennae, and spectrum analyzer required for testing. Usually performed by the site's or vendor's subcontractor.
- Should pay particular attention to RF doors, windows, penetration panels, sinks, cryogen gas exhaust pipes, *etc.*

Siting - RF Shielding

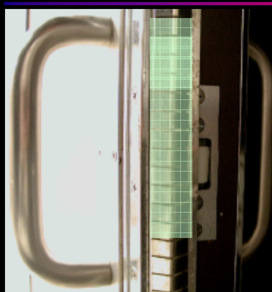
- RF and ground isolation tests should be measured *before* MR system is in place, but *after* as much room construction as possible is complete. A second RF test after all equipment is in place is very useful as a baseline and is recommended.
- Physicist should be present during testing and should receive and maintain certificate of RF shielding performance from vendor or subcontractor.

Siting - RF Shielding

Duct with Baffle Filter

DC Isolation Test and Alarm

RF Shielded Room Door



- The RF door "fingers" provide good electrical contact of the shielded door and the rest of the Faraday cage shield.
- If the fingers are damaged, as they will inevitably be, the effectiveness of the shield decreases and will ultimately give rise to RF interference artifacts (or cause them on an adjacent scanner!).

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Siting – RF Shielding Issues

- To assure integrity of RF shield:
  - Single ground (near penetration panel) – minimize ground loops
  - Dielectric couplers or low pass electrical filters for any conductor that penetrates the shield.
  - All electrical feeds are low pass filtered.
  - Non-conductive connections pass through waveguides.
  - For any conductor that cannot have a dielectric coupler, e.g. medgas lines, fire safety lines, *etc*., they should pass through the shield within a ~2 ft distance from the main shield ground.
- Also:
  - Lighting circuits are typically DC (definitely no fluorescents).

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Phantoms

- A variety of phantoms are required for full acceptance testing of MR scanners.
- Basic geometries: spherical and cylindrical.
- All phantoms should be filled with tissue-mimicking gels or fluids. (Short T_1, ~200-400 ms, improves efficiency.)
- Several useful phantoms (*e.g.*, head and body coil spheres with loading cylinders) are usually maintained onsite by the vendor's service engineers.

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Phantoms

- Several phantoms are, of course, available for purchase from other vendors.
- For sites that undergo the ACR MR Accreditation Program process, the ACR phantom is required and can be used as part of the acceptance testing.
- Some very useful phantoms can be manufactured, based on AAPM guidelines, for quite reasonable prices.

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Phantoms

For "homemade" phantoms, a useful filling material is given by the AAPM acceptance testing document:

- 1 liter H_2O
- 3.6 g NaCl (to simulate conductivity of tissue)
- 1.25 g $CuSO_4$ or 1.96 g $CuSO_4 \cdot 5H_2O$ (to shorten T_1)
- Yields solution with T_1~200ms and σ~0.8 S/cm.

Alternate solution (ACR phantom): 10 mM $NiCl_2$ and 75 mM NaCl. The advantage of using $NiCl_2$ is decreased dependence of T_1 values on temperature as compared to $CuSO_4$.

Phantoms

Some useful phantoms:

- SNR, Uniformity, B_0 Homogeneity, Resonant Frequency Tests
  - Head sphere (~18-20 cm diameter)
  - Body sphere (~30-35 cm diameter)
- Slice Thickness and Spacing Tests
  - Dual high-signal ("hot") crossed ramps (all 3-planes)
- Gradient Field Calibration, Linearity, Geometric Distortion Tests
  - High-contrast, evenly-spaced grids or holes
- High-Contrast Resolution & Low-Contrast Object Detectability Tests
  - Holes or rods of differing sizes and spacings
  - Holes of different sizes in plexiglas sheets of varying thickness (like the ACR phantom)

Phantoms

Vendor Phantoms

Left: Head Sphere with Loading Cylinder

Right: Body Sphere with Loading Cylinder

Left: MDACC Linearity and High Contrast Resolution Phantom

Middle: Vendor DQA Phantom

Right: MDACC Slice Thickness and Spacing Phantom

Phantoms

Image courtesy of Carl Keener, Ph.D.

ACR MR Accreditation Phantom

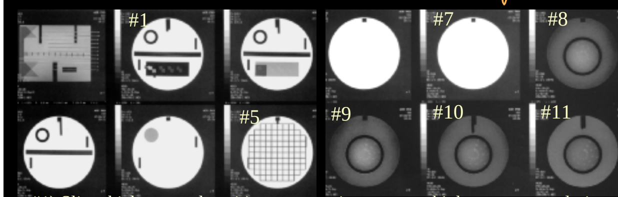
J.M. Specialty Parts
11689-Q Sorrento Valley Road
San Diego, CA 92121
619 794-7200

Large Phantom: $1050

Small Phantom: $ 780 (Ortho)

(as of 1/15/09)

ACR MR Accreditation Phantom



#1) Slice thickness and position, geometric accuracy, high contrast resolution
#5) Geometric accuracy
#7) Percent image uniformity, ghosting
#8-11) Low contrast object detectability, and slice position (in #11)

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General System Checks

Inventory

- RF coils
- Pulse sequences and acquisition modes
- Post-acquisition processing options
- Filming, archiving, network options, RIS/HIS interface, *etc*.
- Patient monitors, injectors, *etc.*
- Computer system IP addresses
- DICOM configuration information

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General System Checks

- Patient safety
  - Patient alert system
  - Patient/console intercom system
  - Table stop buttons (magnet housing and console)
  - Emergency stop buttons
  - Emergency table release mechanism
  - Emergency rundown unit (tested by vendor - trust, but verify)
  - Door switches
- Patient setup and comfort
  - Table docking, raising, lowering, and motion
  - Alignment and bore lights, ventilation systems

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General System Checks

- Table Location Accuracy / Linearity
  - Weight-loaded table with measured *vs* displayed positions.
- Scanner functions
  - Start, Pause, Stop scan buttons on console *and* magnet housing.
  - Filming options and camera interface (SMPTE patterns, *etc*.).
  - Network interface (manual and/or automatic image transfer to other scanners, workstations, archives, *etc*.).
  - Cursor controls, image paging, magnification, *etc.*
  - Basic & advanced image analysis options (*e.g.*, MIP, reformatting)

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General System Checks

Patient monitoring and gating equipment

- Common monitors and interfaces:
  - Peripheral gating interface (pulse oximeter)
  - Respiratory gating interface (bellows)
  - ECG interface and monitor
- Testing of these devices for scanner gating purposes can usually be accomplished by the medical physicist.
- Testing of these devices for critical patient monitoring is best performed by vendor and/or biomedical engineering department, with medical physicist involvement at testing or in review of tests.

General System Checks

MR-compatible power injectors

Becoming more and more common due to expanded uses in

- breath-hold dynamic contrast agent-enhanced (DCE) imaging
- contrast-agent enhanced MR angiography
- dynamic susceptibility change (DSC) "perfusion" imaging

For the injectors and monitoring equipment:

- The systems should be tested with all components "in position" in the scan and operator rooms.
- Installation documents should become part of acceptance tests.

Magnetic Field Homogeneity

- Excellent static magnetic field (B_0) homogeneity is required throughout the active imaging volume.
- Particularly poor homogeneity will result in geometric distortions of images.
- Poor homogeneity will result in areas of inferior fat suppression on large FOV scans when using chemical shift or "fat-sat" lipid suppression techniques.
- Ultrafast imaging and spectroscopy requires higher levels of magnetic field homogeneity than does "routine imaging".

Magnetic Field Homogeneity

- B_0 homogeneity is usually specified in terms of frequency spread (in Hz or ppm) across a given diameter of spherical volume (DSV).

$$FWHM\,(ppm) = \frac{FWHM\,(Hz)}{42576000\,(Hz\,/\,Tesla)\;B_0\,(Tesla)}$$

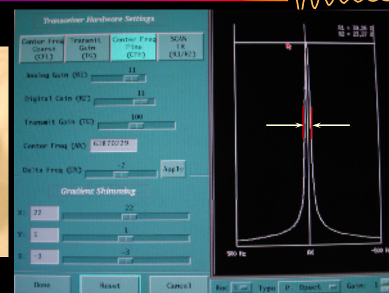
- The required homogeneity depends on the applications of the MR scanner. <u>Possible</u> values are:
  - Routine imaging: ≤ 0.5 ppm RMS at 35 cm DSV
  - Fast imaging (including EPI): ≤ 0.1 ppm RMS at 35 cm DSV
  - Spectroscopy: ≤ 0.1 ppm RMS at 35 cm DSV

Magnetic Field Homogeneity

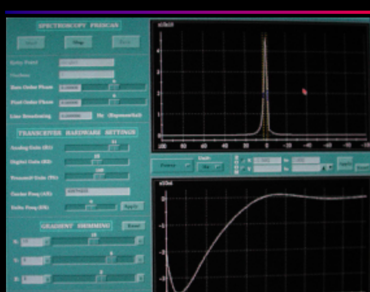
Measurement Technique #1: Spectral peak

- Phantom: Spherical phantom containing doped H_2O with a diameter equivalent to the desired DSV.
- Acquisition: Obtain spectrum from phantom with spectral resolution significantly better than the expected frequency spread.
- Measure the FWHM of the peak to obtain the average homogeneity in Hz (or convert to ppm).
- Advantage: Fast.
- Disadvantages: Can't examine individual planes. Limited DSV values. Some scanners don't have the necessary measurement tools.

Magnetic Field Homogeneity



Magnetic Field Homogeneity



If scanner has spectroscopy capabilities, then the spectroscopy prescan page can be used to easily measure "frequency spread".

Magnetic Field Homogeneity

Measurement Technique #2: Phase mapping

- Phantom: Spherical phantom containing doped H_2O with a diameter larger than the maximum desired DSV.
- Acquisition: Acquire spoiled gradient-echo image with two different echo times separated by a few milliseconds.
- Reconstruct images in "phase image" mode rather than "magnitude image" mode, and subtract the two images.

Magnetic Field Homogeneity

Measurement Technique #2: Phase mapping (cont)

- Inhomogeneity is computed as

$$\Delta B_0 = \frac{\Delta\phi}{\gamma \ (TE_2 - TE_1)}$$

- Disadvantage: Requires ability to reconstruct phase images, ability to subtract them, ability to perform phase "unwrapping", if necessary.
- Advantage: Can assess all planes of interest and various DSVs.

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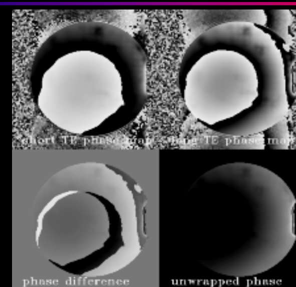
Magnetic Field Homogeneity



Phase Images from GRE Sequences with 10ms Difference in TEs

Phase and Unwrapped Phase Images

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Magnetic Field Homogeneity

- Overall, the phase mapping technique probably provides the best mechanism for routinely evaluating field homogeneity.
- Phase-maps in several planes can be obtained to determine the spherical harmonic coefficients and allows a means of "shimming" the magnet.
- Vendor may provide use of phase-mapping acquisition and analysis tools, or at least the results.
- Suggestion: Obtain a hardcopy of vendor's final homogeneity map and shim coefficients for documentation and baseline.

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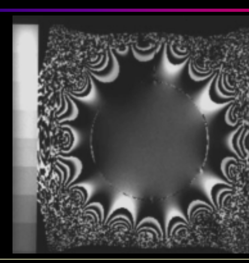
Magnetic Field Homogeneity



LVshim Report
Exam 50196, Series 2, Image 1
(Fri Jan 24 20:35:23 1997)
Scan Bandwidth = 200 Hz
Field of View = 50 cm
Sampling Diameter = 22 cm

Inhomogeneity
3.19 Hz (0.050 ppm)

Harmonic Coefficients given for Z1, Z2, Z3, Z4, Z5, Z6, X, Y, ZX, ZY, X2-Y2, XY, Z2X, Z2Y, ZXY, *etc.*

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Practical Homogeneity Check Method

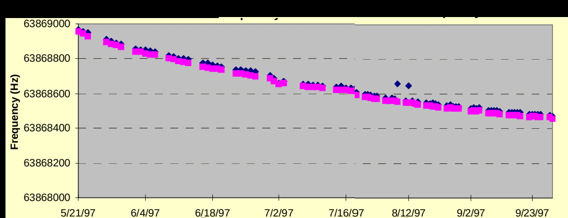
- As the spectral peak and phase mapping techniques have practical limitations for practicing medical physicists, an alternative is a variable bandwidth acquisition technique in a (preferably) spherical phantom.
- Reference:
  - Chen HH, Boykin RD, Clarke GD, Gao JH, Roby JW, *Routine testing of magnetic field homogeneity on clinical MRI systems*, Med Phys 33(11):4299-306 2006.

$$H_B(\text{ppm}) = \frac{\text{BW}_1 \times \text{BW}_2 \times (x_1' - x_2')}{\gamma \cdot B_0 \cdot \text{FOV}_{x2}(\text{BW}_2 - \text{BW}_1)}$$

Magnetic Field Drift

- The measurement of the Larmor frequency (“center frequency”) provides a means of determining the magnetic field strength and monitoring drift.
- ν (Hz) = γ B_0(T), where γ = 42.57 MHz/T for ^{1}H.
- Phantom: Homogeneous phantom containing doped-H_2O preferred; can use ACR phantom.
- Acquisition: Use prescan function to obtain and center spectrum and record the frequency.
- Note: Supercon magnets may exhibit substantial field drift (~10-20 Hz/d) for 1-2 months after installation.
- Criteria: < 1ppm/d or as specified (typically < 0.25 ppm/d later).

Magnetic Field Drift



Magnetic Field Drift

- Non-supercon magnets also drift (on shorter time scale).
- Temperature dependent drift is particularly important for non-supercon systems. (Temperature variation of any passive shielding material can also cause B_0 fluctuation.)
- Should determine transmit frequency several times during the day during acceptance testing to assess any B_0 drift.

RF Subsystem Tests

RF Calibration

- Acquire images with minimal slice gap using primary pulse sequences and look for central zipper artifacts and ghost images which may indicate RF calibration or hardware problems.
- Check to see if the "autoprescan" values for transmit and receive gains match what you determine manually.
- For gradient-echo sequences, repeat the sequence for several values of nutation angle and plot signal intensity *vs* nutation angle (should show sinusoidal dependence, max @ 90^o, zero @ 180^o). (Use TR >> T_1.)

RF Subsystem Tests

RF Stability

- Suggestion: Use vendor's field service tools to record frequency and phase stability in all three axes. (Gradient instabilities and eddy currents also are important factors.)
- Generally a sensitive indicator for upcoming problems.

RF Subsystem Tests

RF Stability

Z AXIS STABILITY

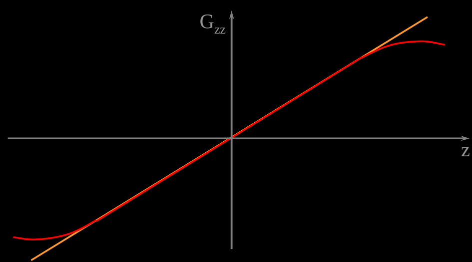
Echo Pos. (msec)	Mag. Drift P-P (%)	Mag. Drift RMS	Freq. Drift P-P (Hz)	Freq. Drift RMS	Phase Drift P-P (Deg)	Phase Drift RMS
3.69	0.53	0.11	1.40	0.32	2.75	0.53

Gradient Subsystems Tests

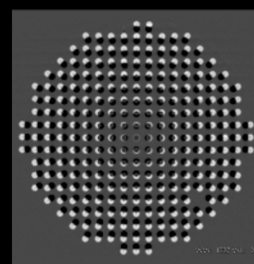
Distance Accuracy and Geometric Distortions

- The primary factors influencing geometric distortions in MRI are gradient field nonlinearity and, to a much lesser degree, B_0 field nonuniformity.
- Even with the significant effort to design highly linear gradient fields, vendors must still utilize a post-acquisition correction algorithm, *e.g.*, "gradwarp", to minimize distortions due to gradient nonlinearities.
- B_o field inhomogeneity can become significant as one moves further from magnet isocenter or uses very low bandwidth.

Gradient Field Nonlinearities



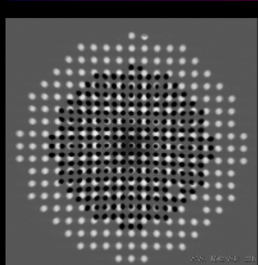
Gradient Field Nonlinearity Effects In-Plane Distortion



Slice Plane at Isocenter

- 20 cm FOV
- White circles: with gradient non-linearity correction
- Black circles: without gradient non-linearity correction
- Maximum error without correction: ~ 4.5 mm at ±10 cm from isocenter
- Maximum error with correction: < 1 mm at ±10 cm from isocenter

Gradient Field Nonlinearity Effects In-Plane Distortion



Slice Plane at 20 cm from Isocenter

- 20 cm FOV
- White circles: with gradient non-linearity correction
- Black circles: without gradient non-linearity correction
- Maximum error without correction: ~ 5.5 cm at ±10 cm from isocenter
- Maximum error with correction: < 2 mm at ±10 cm from isocenter

Gradient Subsystems Tests

Distance Accuracy and Linearity Tests

- Phantom: High contrast grid or hole pattern or other phantom with accurately known high contrast physical dimensions.
- Acquisition: Spin-echo, T_1-weighted images provide good quality images in a reasonable time. 3 principal planes, on- and off-isocenter. Cover adequate volume for application (particularly if using images for image-guided therapy)
- Analyses (in all 3 principal planes):
  - Distance accuracy
  - Geometric distortion
  - Coefficient of variation of spacing of holes/grid (linearity test)

Gradient Subsystems Tests

Distance Accuracy and Linearity Tests (cont.)

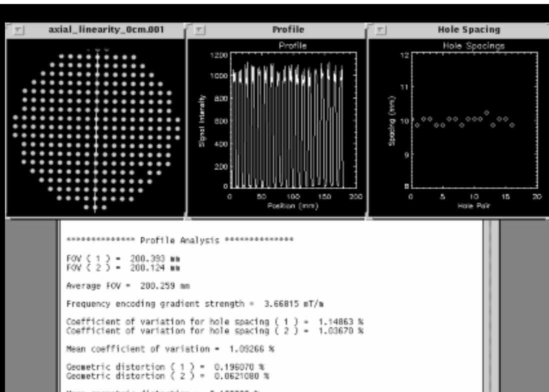
– Distance Accuracy Test
  - Δ_{meas} *vs* Δ_{actual}
  - Can also verify accuracy of reported FOV and scanner's built-in distance measurement tools. (Important if such tools are to be used for later acceptance tests.)

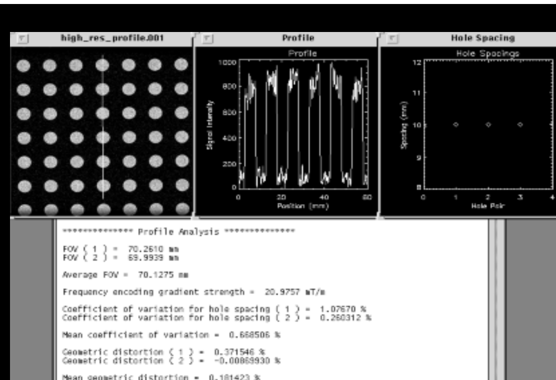
– Geometric Distortion (per AAPM TG-6)
  - $\%GD = 100 \cdot (\Delta_{actual} - \Delta_{meas}) / \Delta_{actual}$
  - Compute in each direction for each plane.
  - Criteria: Should not exceed 2%.

Gradient Subsystems Tests

Distance Accuracy and Linearity Tests (cont.)

– Linearity
  - $\%CV = 100 \cdot \sigma(\Delta_{meas}) / \bar{\Delta}_{meas}$
  - Compute in each direction for each plane.
  - Gives more complete description of gradient linearity *within* FOV.



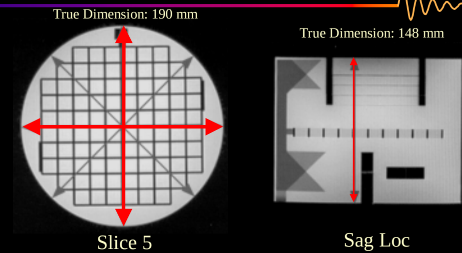


Gradient Subsystem Tests

GRADCAL

Axis	Diameter (mm)	Center (mm)
X	170.1	2.1
Y	170.0	-8.8
Z	169.8	-1.4

Gradient Subsystem Tests



Set WW & WL to min, then raise WL until 1/2 water is dark (*mean*)
Set WW to *mean* and WL to 1/2(*mean*)

Criteria: ± 2 mm

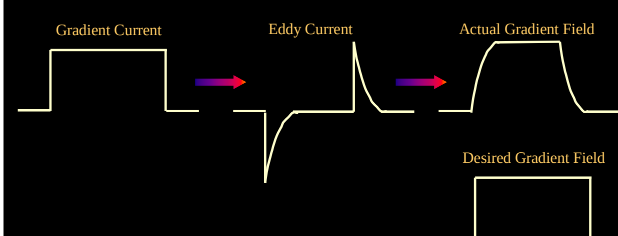
Gradient Subsystems Tests

Eddy Current Evaluation

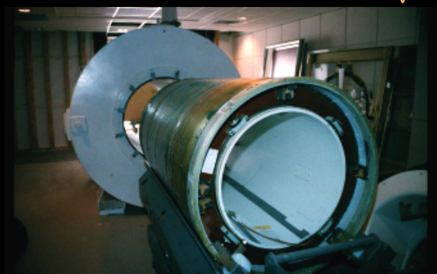
– Eddy currents produce transient magnetic fields that oppose the applied linear gradient fields. Difficulties in obtaining very rapid gradient switching rates are primarily due to these fields and can limit fast imaging applications, particularly EPI, and have a strong detrimental effect on MRS.

– Most high-field system manufacturers now produce “actively shielded” gradient systems consisting of two concentric coils. The outer coil serves to cancel the magnetic field gradient outside the two coils while maintaining linearity inside the inner coil.

Eddy Currents



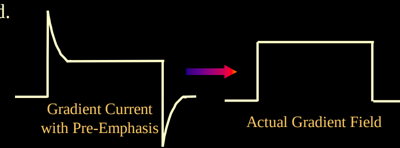
Gradient Subsystems



Gradient Subsystems Tests

Eddy Current Evaluation (cont.)

Even with active shielding, many vendors still compensate for eddy currents during installation by adding a multiexponential component to the desired gradient waveform ("pre-emphasis"). Typically, short, medium, and long term time constants are used.



Gradient Subsystems Tests

Eddy Current Evaluation (cont.)

- The eddy current evaluation, while important, is difficult to independently obtain given commonly available measurement tools.
- Suggestion: Maintain hardcopy of vendor's final eddy current calibration tests.
- Note: Diffusion-weighted EPI scans and/or spectroscopy scans can also be useful indirect means of assessing eddy current compensation, if the scanner has such capabilities.

Gradient Subsystems Tests

Eddy Current Evaluation (cont.)

Time (ms)		B0=X	G1=X	G2=Y
Start	End	B0	G1	G2
2.3	11.3	0.052	0.008	-0.030
21.0	30.0	0.035	0.011	-0.021
41.0	50.0	-0.013	-0.000	-0.017
91.0	100.0	0.026	-0.009	-0.008
Time (ms)		B0=Y	G1=Y	G2=Z
Start	End	B0	G1	G2
2.3	11.3	-0.058	0.004	0.060
21.0	30.0	-0.047	0.013	0.043
41.0	50.0	-0.057	-0.002	0.031
91.0	100.0	-0.032	-0.018	0.013
Time (ms)		B0=Z	G1=Z	G2=X
Start	End	B0	G1	G2
2.3	11.3	0.008	-0.012	-0.007
21.0	30.0	0.014	-0.001	-0.004
41.0	50.0	0.020	0.001	-0.005
91.0	100.0	-0.001	-0.009	-0.004

Combined RF/Gradient Tests

Slice Thickness

- The slice thickness in MRI is ideally determined by the gradient amplitude and the bandwidth of the slice-selective RF pulse, *i.e.*, $\Delta z = \Delta\omega / (\gamma G)$.
- Slice thickness is influenced by gradient field nonuniformity, RF field nonuniformity, RF pulse shape, and TR/T_1 ratio.
- Several phantoms have been designed to measure slice thickness and are commercially available. These include "step" designs, spiral "corkscrew" designs, and, most commonly, ramps.

Combined RF/Gradient Tests

Slice Thickness (cont.)

- Measurement Method: "Hot" Ramp Phantom
- Phantom:
  - Crossed-ramp phantom filled with doped-H_2O such that $T_1 \leq$ 250 ms. (Crossed-ramps correct for a tilted phantom placement in the scanner.) Use $TR \geq 3T_1$.
  - Width of ramp material should be small w.r.t. minimum slice thickness desired.
  - If a and b are the measured FWHM values on each of one set of ramps, then, for orthogonal ramps, the average FWHM is $\sqrt{ab}$.

Combined RF/Gradient Tests

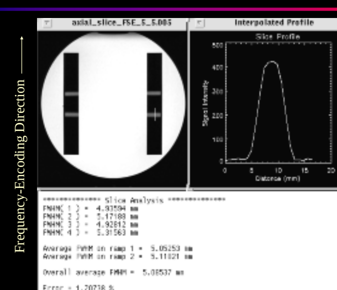
Slice Thickness (cont.)

- For arbitrary angle, ϕ, between ramps:

$$FWHM = \frac{(a+b)\cos\phi + \sqrt{(a+b)^2\cos^2\phi + 4ab\sin^2\phi}}{2\sin\phi}$$

- Note: Accuracy of measurement depends on thickness of the ramp material and angle of the ramps. The thinner the ramp material, the more accurate BUT lower SNR.
- For a 90° ramp at 45° to scan plane, the ramp thickness should be <20% of the slice FWHM, *i.e.*, a 5 mm slice needs a 1 mm ramp to have error <20%.
- Criteria: ±10% for prescribed slice thickness ≥5mm (T_1W SE)

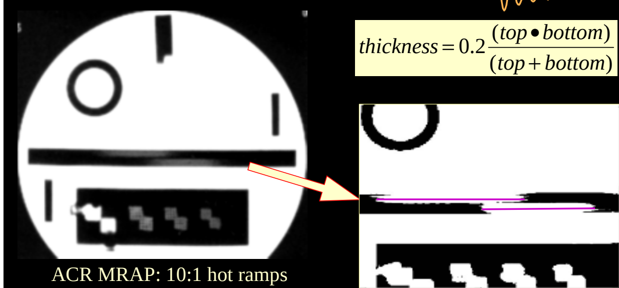
Combined RF/Gradient Tests



Acquisition matrix:
512x256

Combined RF/Gradient Tests

$$thickness = 0.2\frac{(top \bullet bottom)}{(top + bottom)}$$



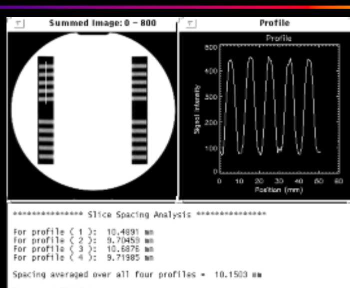
ACR MRAP: 10:1 hot ramps

Combined RF/Gradient Tests

Slice Spacing

- The separation between slices in MRI is ideally determined by the difference in center frequency of the RF pulse and the slice-selection gradient amplitude.
- Separation can be determined using either of the methods outlined for slice thickness measurement.
- Criteria: Disagreement ≤ 10% of the prescribed separation for SE T_1W sequence.

Combined RF/Gradient Tests



Global System Tests

Signal-to-Noise Ratio

- SNR is influenced by slice thickness, pixel size, pulse sequence, sampling bandwidth, RF coil (design, tuning, loading), TE, TR, number of averages…essentially everything.
- Must set and consistently use all parameters on all scanners and on each run.
- Criteria: Should agree with vendor's specified values. Problem: Vendor probably does not use similar means of determining SNR. Also, many vendors do not provide SNR specs for coils.

Global System Tests

Signal-to-Noise Ratio (cont.)

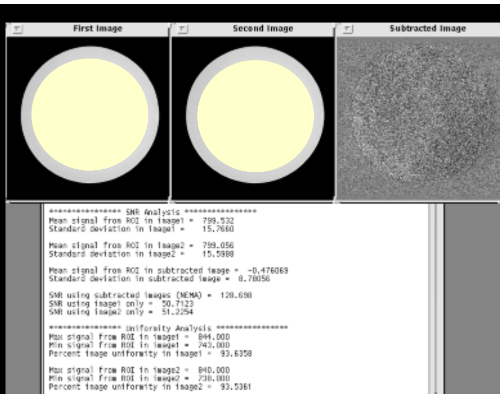
- AAPM suggested measurement is the NEMA approach (MS1).
- Phantom: Uniform doped-H_2O sphere or cylinder.
- Acquisition: Two images of same location using *identical* acquisition parameters. Repeat for all planes.
- Analysis: Subtract the images, use an ROI that encompasses at least 75% of the phantom, then

$$SNR_{NEMA} = \frac{\sqrt{2}\ \bar{S}}{\sigma_{diff}}$$

where S is the signal in the large ROI and σ_{diff} is the standard deviation of the noise in the same ROI in the difference image.

Global System Tests

Head (16.8cm) and Body (26.6cm) Spheres with Loading Cylinders



Global System Tests

Signal-to-Noise Ratio (continued)

- Some scanners do not allow for calculation of difference images.
- Single image SNR can be determined from the same signal ROI, along with a noise ROI in the background (air). Make sure noise ROI excludes any ghosting.

$$SNR = \frac{\bar{S}}{\left[\sigma_{bkg} / \sqrt{2 - \frac{\pi}{2}}\right]} \approx \frac{0.655\ \bar{S}}{\sigma_{bkg}}$$

- Factor of 0.655 accounts for Rician distribution in low signal areas of magnitude images (Gudbjartsson and Patz, Magn Reson Med 34:910, 1995).

Global System Tests

Noise	Inoise	Qnoise		
2.83	2.98	2.83		
Pk VB Sig	Av VB Sig	Pk B1 Sig	Av B1 Sig	
8269.67	6539.99	14.24	3.58	
Plane	Signal	SNR	Area	Hot Pixel
Ax	296.8	104.7	25700	318
Sag	295.4	104.2	25006	317
Cor	292.2	103.0	24825	316
SNR Histograms				
Plane	Max	Mean	St Dev	
Ax	19.0	9.0	7.71	
Sag	20.0	7.6	6.93	
Cor	18.0	7.1	6.10	

Global System Tests

- SNR measures should be obtained for:
  - Head Coil
  - Body Coil
  - Surface Coils (Suggest maximum SNR measures as outlined in Section IV.D.3 of the Medical Physicist/MRI Scientist section of the *ACR MRI Quality Control Manual 2004*)
- If time permits, measures of SNR in all three planes for at least one pulse sequence for head and body coils are useful, as are measures for all major pulse sequences in a single coil and plane.

Global System Tests

Percent Image Uniformity

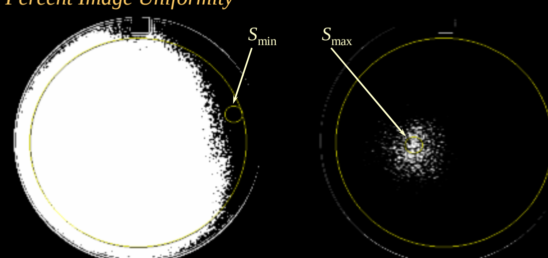
- Affected by B_1 inhomogeneities, B_0 inhomogeneities, eddy currents, and gradient uniformity.
- Phantom: Uniform phantom used for SNR tests.
- Acquisition: With phantom occupying ≥80% of FOV, use SE sequence. Repeat for all 3 principal planes.
- Analysis: Use ROI enclosing at least 75% of image

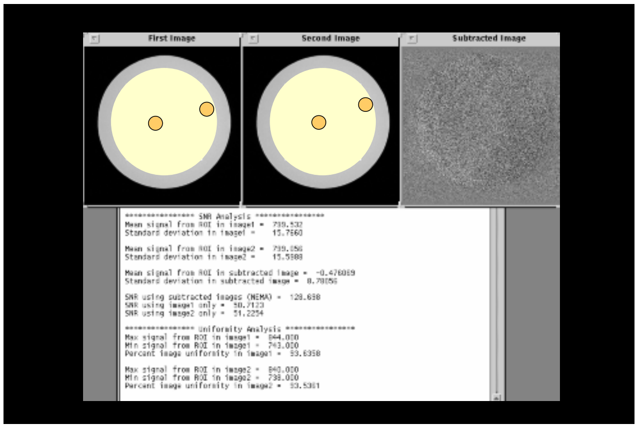
$$PIU = 100 \bullet \left[1 - \frac{(\bar{S}_{max} - \bar{S}_{min})}{(\bar{S}_{max} + \bar{S}_{min})}\right]$$

- Criteria: PIU ≥ 90%.

Global System Tests

Percent Image Uniformity

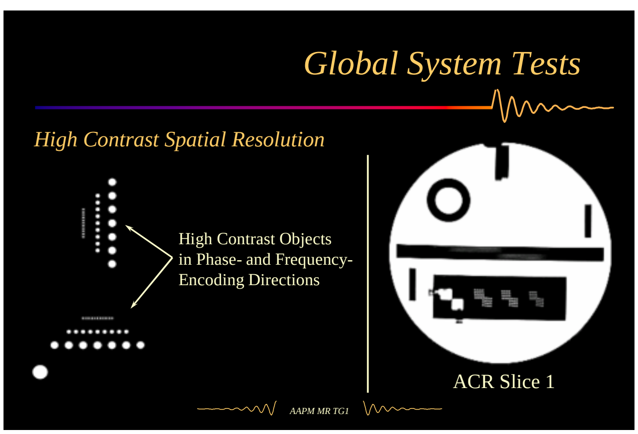


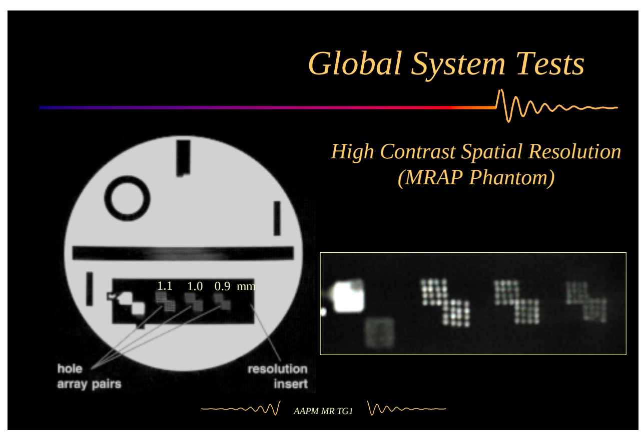


Global System Tests

High Contrast Spatial Resolution

- Most commonly assessed with a phantom containing successively smaller high contrast objects.
- Criteria: Should be able to resolve object sizes that are at least one (theoretical) pixel width in size.





Global System Tests

Low Contrast Object Detectability

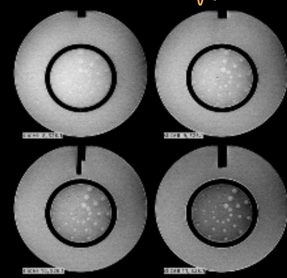
- Not discussed in either AAPM document. However, the ACR accreditation phantom does have a low contrast detectability section (4 disks of varying thickness with varying diameter holes).
- Typical criteria for ACR T1 series: 40 spokes at 3.0T, ≥36 spokes at 1.5T, ≥32 spokes at 1.0T, ≥23 spokes at 0.5T, ≥11 spokes at 0.3T, and ≥6 spokes at 0.2T.

Global System Tests

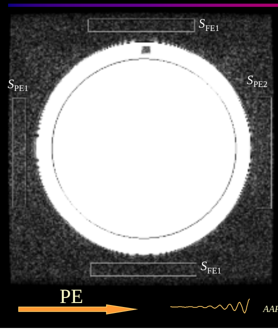
Low Contrast Object Detectability

(ACR Phantom)

Slice 8:	1.4%
Slice 9:	2.5%
Slice 10:	3.6%
Slice 11:	5.1%



Global System Tests



Ghosting Ratio

$$GR = \left| \frac{(\bar{S}_{PE1} + \bar{S}_{PE2}) - (\bar{S}_{FE1} + \bar{S}_{FE2})}{2\ \bar{S}} \right|$$

Sequences: T_1W SE and T_2W FSE

Criteria: ≤ 0.001 (ACR: 2.5%)

Special Applications

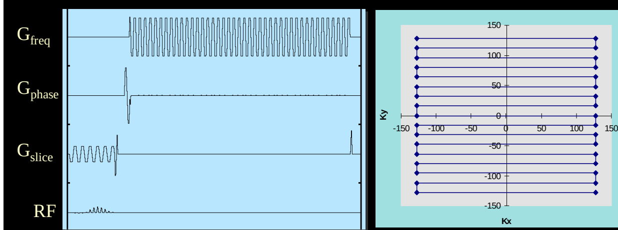
Special applications might include:

- Echo-planar acquisitions for functional imaging (diffusion imaging, neuronal activation mapping, perfusion imaging, *etc.*)
- *In vivo* MR spectroscopy
- Acquisition of data for image-guided therapy (surgical, radiosurgical, IMRT, *etc.*)

"Ultra-Fast" Imaging QA Issues

- High-speed imaging techniques that rapidly acquire a "train" of uniquely phase-encoded echoes each TR period are susceptible to several additional forms of artifacts. The artifacts worsen as the "echo train length" (ETL) increases. (Longer ETL => faster image acquisition times.)
- Ultra-fast sequences, such as echo planar imaging (EPI), are even more susceptible to such artifacts.

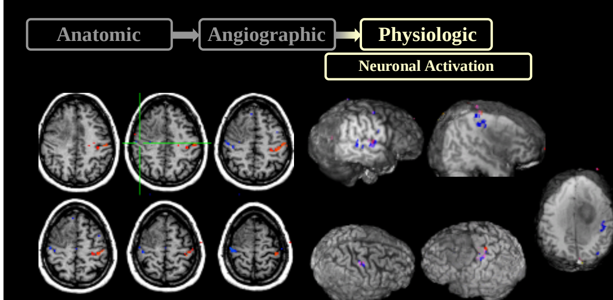
Echo Planar Imaging



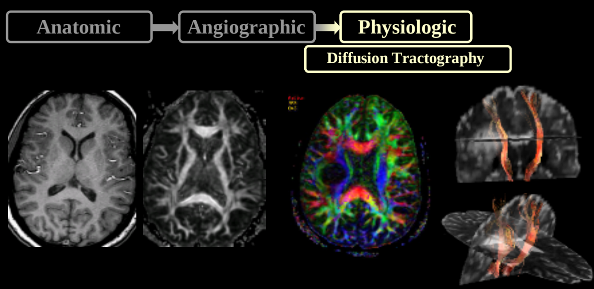
Echo-Planar Imaging Tests

- Echo-planar imaging (EPI) is the most widely utilized sequence for obtaining MR images extremely rapidly (down to 50 ms/image).
- There are no established guidelines for EPI acceptance tests or quality assurance.
- In "single-shot EPI", all frequency- and phase-encodings are performed in a single TR. Accomplishing this requires extremely fast switching of the gradients and high sampling bandwidth (~100-250 kHz, often analog).

MR Imaging Biomarkers



MR Imaging Biomarkers



EPI Acceptance Testing

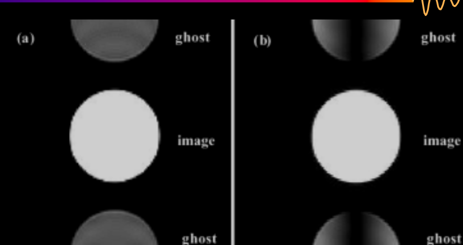
EPI Acceptance Tests

- Similar tests performed for "conventional" pulse sequences can be repeated for EPI, including geometric distortion, ghosting, and SNR.
- Signal stability is particularly important for systems to be utilized for fMRI studies, and should be assessed.
- In addition, it is useful to assess the "signal-to-ghost ratio" (SGR). The ghosts occur in the phase-encoding direction and are primarily due to phase errors accumulated during the scan. If the FOV is small compared to the anatomy, the ghosts will alias onto the anatomy.

EPI Acceptance Testing

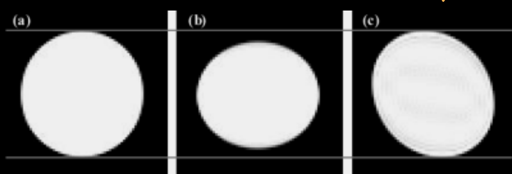
- Distortion and shift
  - B_0-field inhomogeneity or susceptibility-induced
  - eddy currents (especially in diffusion imaging)
  - off-resonance effects (chemical shift, magnetic susceptibility variations, *etc.*)
- Ghosting
  - eddy currents
  - asymmetric filter response of analog RF receivers

EPI Acceptance Testing



N/2 EPI ghosts due to (a) zeroth-order and (b) first-order phase shifts (note signal null in center of ghost image)

EPI Acceptance Testing



Spin echo image without geometric distortion (a), EPI image with compression distortion (b), and EPI image with shear distortion (c)

EPI Acceptance Testing

- Evaluate geometric distortion (shift and distortion)
- Evaluate the ghost levels

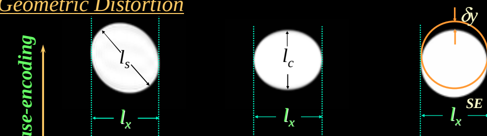
EPI Acceptance Testing

Geometric Distortion and Ghosting

- Phantom
  - Uniform sphere with a diameter of ~10-15 cm
- Acquisition protocol
  - Single-shot EPI (typically a SE-EPI diffusion sequence)
  - TR ≈ 5000 ms, TE ≈ 100 ms
  - FOV = 24 cm, 5 mm slice
  - 128 x 128 matrix

EPI Acceptance Testing

Geometric Distortion



shear factor $\frac{|l_s - l_x|}{l_x}$

compression or dilation factor $\frac{|l_c - l_x|}{l_x}$

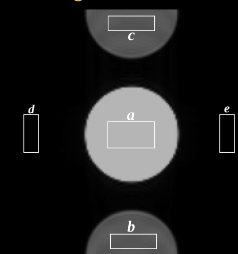
shift factor $\frac{|\delta y|}{l_x}$

Images courtesy of X. Joe Zhou, PhD

Current criteria: 3-4%

EPI Acceptance Testing

Ghosting



Measurement of the average signal-to-ghost ratio. ROIs *b* and *c* provide measurements of ghost signal intensity and ROIs *d* and *e* are provide measurements of background (noise) signal intensity.

$$GSR = \left| \frac{(\bar{S}_b + \bar{S}_c) - (\bar{S}_d + \bar{S}_e)}{2\ \bar{S}_a} \right|$$

Current proposed criteria: 3%

AAPM MR TG1

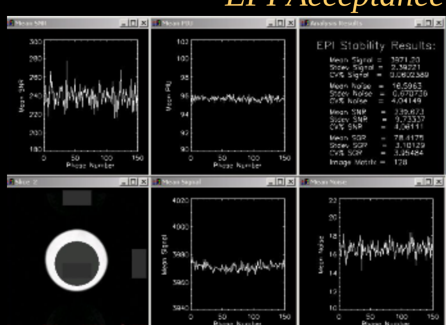
EPI Acceptance Testing

Signal Stability

- Phantom
  - Uniform sphere with a diameter of ~10-15 cm
- Acquisition protocol
  - Single-shot EPI (typically a GR-EPI BOLD sequence)
  - TR ≈ 4000 ms, TE ≈ 50 ms, α=90º
  - FOV = 24 cm, 5 mm slice
  - 128 x 128 matrix
  - 150 repetitions (10 min)

AAPM MR TG1

EPI Acceptance Testing

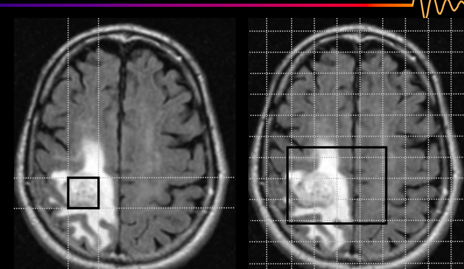


Current criteria:

0.25% variation

AAPM MR TG1

Localization Techniques

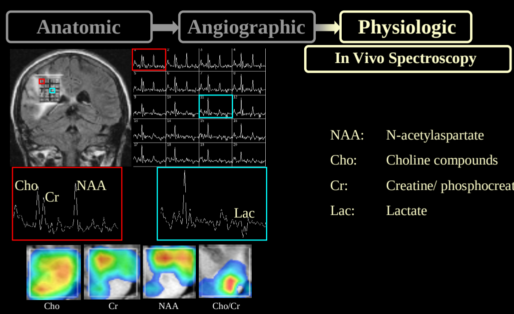


Single Voxel

Spectroscopic Imaging

AAPM MR TG1

MR Imaging Biomarkers



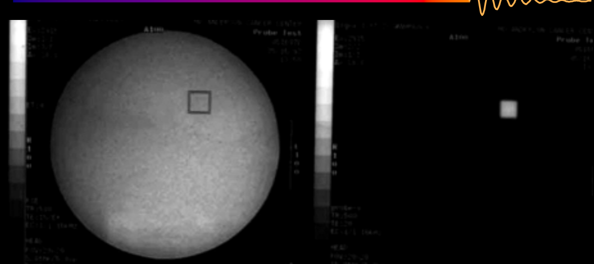
NAA: N-acetylaspartate
Cho: Choline compounds
Cr: Creatine/ phosphocreatine
Lac: Lactate

MR Spectroscopy Tests

If the system has MRS capability, some basic acceptance tests to perform include:

– VOI location accuracy (SV)
  - Acquire localized VOI images in several locations (isocenter and displacements in all three directions) and compare to prescribed locations.
– Automated shimming tests (SV and SI)
  - Assess the quality of automated shimming parameters based on the unsuppressed water peak and the water-suppressed metabolite peak linewidths.

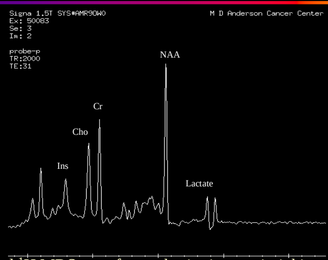
MR Spectroscopy Tests



MR Spectroscopy Tests

– H_2O suppression efficiency tests (SV and SI)
  - Can obtain from phantom containing doped-H_2O and small quantity of MR-visible compound with known chemical shift w.r.t. water resonance. Multiple compounds with variable chemical shifts are better.
– SNR tests (SV and SI)
  - Obtain SNR measures from localized spectrum in a uniform phantom.

MRS Acceptance Testing



Water-suppressed ^{1}H MRS scan from a brain tissue mimicking phantom. NAA: *N*-acetylaspartate, Cr: creatine and phosphocreatine, Cho: choline, Ins: *myo*-inositol

Final Acceptance Test Procedure

As the final step in the MR acceptance testing procedure, obtain one or two sets of data using the acquisition parameters and analysis that will be used for daily quality assurance (baseline data).

- Resonant frequency
- Slice thickness and spacing
- High contrast resolution / low contrast object detectability
- Distance accuracy and geometric distortion
- SNR
- Image Uniformity

Also, acquire ACR MRAP scans and initial baseline ACR QC data.