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# *MRI Acceptance Testing*

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## *Outline*

- Testing guidelines and a reality check.
- Phantoms for acceptance testing.
- Siting tests, *i.e.*, magnetic and RF shielding.
- General system checks.
- Magnet subsystem tests.
- RF subsystem tests.
- Gradient subsystem tests.
- Combined RF/Gradient tests.
- Global system tests.
- Testing of optional equipment, *i.e.*, EPI and MRS.

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## *Testing Guidelines*

Primary MRI acceptance testing 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.

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## *Levels of Involvement*

- 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
- As always, documentation is critical.

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## *MR Acceptance Test Reality Check*

- System specifications. Golden rule: "Don't spec what you can't test."
- 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 RF coils. Just how much do I test?
- What are the unique applications of the MR systems at the particular site?

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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, preferably with fairly short $T_1$.
- Several useful phantoms (*e.g.*, head and body coil spheres with loading cylinders) are usually maintained onsite by vendor's service engineers.

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## *Phantoms*

- Several phantoms are, of course, available for purchase from other vendors.
- For sites who are undergoing the ACR MR Accreditation Program process, the ACR phantom is required.
- Some very useful phantoms can be manufactured based on AAPM guidelines at 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 $\sigma$~0.8 S/cm.

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## *Phantoms*

Some useful phantoms are:

- SNR, Uniformity, $B_0$ Homogeneity, Resonant Frequency Tests
  - Head sphere (~18-20 cm diameter) with cylindrical loader.
  - Body sphere (~30-35 cm diameter) with cylindrical loader.
- Slice Thickness and Spacing Tests
  - Dual high-signal crossed ramps (all 3-planes)
- Gradient Field Calibration, Linearity, Geometric Distortion Tests
  - High-contrast, evenly-spaced grids or holes.
- High- and Low-Contrast Spatial Resolution Tests
  - Holes or rods of differing sizes and spacings.
  - Holes of different sizes in plexiglas sheets of varying thickness (á la ACR).

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## *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

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## *Siting - Magnetic Field Shielding*

- Fringe fields should be mapped on site drawings.
- 5 G lines should be carefully mapped and posted using appropriate signage (multilingual as needed). Any persons with cardiac pacemakers or neurostimulators should not enter the 5 G area.
- 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]).

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## *Siting - RF Shielding*

- Typical attenuation values: ~100dB at 100 MHz for 1.5T systems.
- RF signal generator, amplifier, transmission and reception antennae, and spectrum analyzer required. Therefore, testing is usually performed by vendor or site's/vendor's subcontractor.
- Should pay particular attention to doors, windows, penetration panels, sinks, *etc.*

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## *Siting - RF Shielding*

- In addition to RF attenuation, most vendors specify the minimum ground isolation of the shield from building ground at DC, *e.g.*, 1000Ω.
- If possible, RF and ground isolation tests should be measured *before* MR system is in place, but *after* all room construction is complete. A second RF test after all equipment is in place is useful as a baseline.
- Physicist should be present during testing and should receive and maintain certificate of RF shielding performance from vendor or subcontractor.

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## *General System Checks*

- Inventory
- Patient safety
  - Patient alert system
  - Patient/console intercom system
  - Table stop button (magnet housing and console)
  - Emergency stop buttons
  - Emergency table release mechanism
  - Emergency rundown unit (tested by vendor)
  - 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 and advanced image analysis options (MIP, reformatting, *etc*.)

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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.
  - End tidal $CO_2$ monitor.
- Testing of these devices for gating can usually be accomplished by the medical physicist.
- Testing of these devices for critical patient monitoring is probably best performed by vendor and/or biomedical engineering department, with medical physicist involvement at testing or in review of tests.

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## *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).
  $\Delta B_0$ (ppm) = $\Delta B_0$ (Hz) / [42.576•$B_o$(T)]
- The required homogeneity depends on the applications of the MR scanner. Possible values are:
  – Routine imaging: ≤5 ppm at 35 cm DSV
  – Fast imaging (including EPI): ≤1 ppm at 35 cm DSV
  – Spectroscopy: ≤0.5 ppm at 35 cm DSV
- Criteria (AAPM): Typical: 10 ppm for 30-40 cm DSV

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## *Magnetic Field Homogeneity*

Measurement Technique #1 - Spectral Mapping

– Phantom: Small doped $H_2O$ sample.
– Acquisition: Obtain MR spectrum from sample at multiple locations.
– Disadvantage: Tedious and slow, requires spectral acquisitions.
– Advantages: Accuracy (if performed with care). Can map field into spherical harmonics for “shimming”.

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## *Magnetic Field Homogeneity*

Measurement Technique #2: 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 homogeneity in Hz (or convert to ppm).
– Advantage: Fast.
– Disadvantages: Need software tools to measure FWHM accurately. Can’t examine individual planes. Limited DSV values.

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## *Magnetic Field Homogeneity*

Measurement Technique #3: 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 TE~30 ms, then acquire a second spoiled gradient-echo image with TE~35 ms.
– Reconstruct images in “phase image” mode rather than “magnitude image” mode, and subtract the two images.
– $\Delta B_0 = \Delta\phi / [\gamma (TE_1 - TE_2)]$ on pixel-by-pixel basis.
– Disadvantage: Requires ability to reconstruct phase images, ability to subtract them, ability to perform phase “unwrapping”.
– Advantage: Can assess all planes of interest and various DSVs.

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## Magnetic Field Homogeneity

- Overall, the phase mapping technique provides the best mechanism for 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.
- MDACC: Filmed copy of vendor's final homogeneity map and shim coefficients for documentation and baseline.

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## Cryogen Consumption

- Older MR systems utilized liquid nitrogen to cool the liquid helium. On such systems, "boiloff" rates for both should be obtained.
- Newer systems use only liquid helium with a "cold head" compressor in place of the liquid nitrogen.
- Some vendors now have sensing units that automatically report cryogen levels.
- Warning: Boiloff rates require several weeks to stabilize after installation and after any refill or supercon shim procedure.

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## Larmor Resonance Frequency

- The measurement of the Larmor frequency ("center frequency") provides a means of determining the magnetic field strength and monitoring drift.
- $\nu$ (Hz) = $\gamma \cdot B_0$(T), where $\gamma$ = 42.57 MHz/T for $^1$H.
- Phantom: Large diameter homogeneous sphere containing doped-$H_2O$.
- Acquisition: Use prescan function to obtain and center spectrum and record the frequency.
- Warning: Supercon magnets may exhibit substantial field drift (~10-20 Hz/d) for 1-2 months after installation.
- Criteria (AAPM): <3ppm/d or as specified.

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## RF Subsystem Tests

*RF Calibration*

- AAPM TG6: Acquire images with minimal slice gap using range of pulse sequences and look for central zipper artifacts and off-center 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.
- AAPM TG6: 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$^o$).

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## RF Subsystem Tests

*RF Stability*

- AAPM TG6: "Place a uniform phantom at isocenter, and select a pulse sequence in which only slice-select gradients and RF pulses are used. Observe the FID using a TR of 1000ms." Repeated FIDs should show little fluctuation. Any fluctuation could be due to either frequency or phase drift. (Make sure TR > $5T_1$.)
- MDACC: 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.

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## Gradient Subsystems Tests

*Distance Accuracy and Geometric Distortions*

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

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## Gradient Subsystems Tests

*Distance Accuracy and Linearity Tests*

- Phantom: High contrast grid or hole pattern.
- Acquisition: Spin-echo, $T_1$-weighted images, provide good quality images in reasonable time. 3 principal planes, on- and off-isocenter.
- MDACC: SE, TE/TR=20/500ms, 5mm, 256x256, 2 NEX Axial: isocenter, 6cm, 15cm, 21cm. Sag/Cor: isocenter, 6cm.
- Analyses (in all 3 principal planes):
  - Distance accuracy
  - Geometric distortion (AAPM)
  - Coefficient of variation of spacing (linearity test)
  - Frequency-encoding gradient strength

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## Gradient Subsystems Tests

*Distance Accuracy and Linearity Tests (cont.)*

- Distance Accuracy Test
  - $<\Delta_{meas}>$ *vs* $<\Delta_{actual}>$
  - 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 NMR TG-6)
  - $\%GD = (<\Delta_{actual}> - <\Delta_{meas}>) / <\Delta_{actual}> \cdot 100$
  - Compute in each dimension for each plane.
  - Criteria (AAPM): Should not exceed 5%. Typically <2%.

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## Gradient Subsystems Tests

*Distance Accuracy and Linearity Tests (cont.)*

- Linearity (MDACC)
  - %CV = $\sigma(\Delta_{meas}) / \langle\Delta_{meas}\rangle \bullet 100$
  - Compute in each dimension for each plane.
  - Gives better description of gradient linearity within FOV.
- Frequency-encoded gradient strength
  - $G_r$ = SW (Hz) / ($\gamma \bullet$ FOV)
  - SW = spectral width = $N_{pts} / t_{acq}$, where $N_{pts}$ is the number of frequency-encoded points and $t_{acq}$ is the acquisition time for a single echo, or obtain SW from scanner.
  - Maximum gradient strength should be obtained (per AAPM TG6), by using smallest FOV possible.

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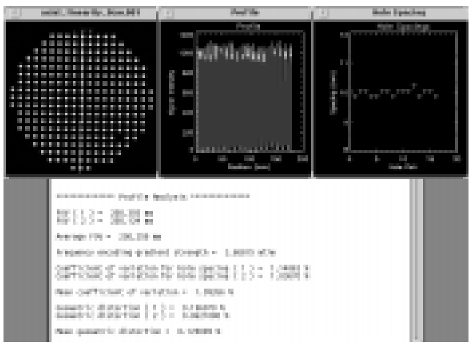

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## Gradient Subsystems Tests

*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.
- Most manufacturers now produce “actively shielded” gradient coils that are two concentric coil systems. The outer coil serves to cancel the magnetic field gradient outside the two coils while maintaining linearity inside the inner coil.
- Even with active shielding, many vendors still compensate for eddy currents during installation by adding a multiexponential component to the desired gradient waveform. Typically, short, medium, and long term time constants are used.

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## Gradient Subsystems Tests

*Eddy current evaluation (cont.)*

- Method 1: Integrator circuit (AAPM TG6)
  - Small pickup coil with integrating amplifier to measure gradient switching rate.
  - Integrating amplifier must exhibit fast response and very small drift over time to characterize fast, medium, and long time components.
  - With faster and faster switching rates, this technique has become more and more difficult.
  - Criteria (AAPM): Rise/Fall times should meet spec.

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## Gradient Subsystems Tests

*Eddy current evaluation (cont.)*

- Method 2: Effect on signal from sample (AAPM TG6)
  - Use uniform phantom with a pulse sequence having a gradient pulse (5-20 ms duration), followed by a delay, D, and a 90º RF pulse and FID acquisition.
  - Compute area of spectral peak for values of D ranging from 100 ms down to 1 ms. The value of D at which the peak area begins to decrease is a *relative* measure of eddy current effects. Repeat for all three gradient axes.
  - Useful indirect measure, but requires pulse programming tools and expertise as well as peak area calculations.
  - Criteria (AAPM): Area constant until D≤3ms.

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## Gradient Subsystems Tests

*Eddy current evaluation (cont.)*

- In my experience, the eddy current evaluation, while important, is difficult to independently obtain given commonly available measurement tools.
- MDACC: Maintain filmed copy of vendor's final eddy current calibration tests.

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## 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.

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## Combined RF/Gradient Tests

*Slice Thickness (cont.)*

- Method 1: Frequency Profile Measurement (AAPM TG6)
- Phantom: Homogeneous sphere/cylinder, $T_1 \leq 200$.
- Use pulse sequence that allows slice selection and frequency-encoding along the same axis. Then the Fourier transform of the acquired echo is the slice profile (in frequency units). Use $TR \geq 3T_1$ of phantom.
- Advantage: Can assess thin slices, and examine spatial variation of slice thickness (if 2D image is formed).
- Disadvantage: Requires custom pulse sequences, one for each type of acquisition of interest (SE, GRE, *etc.*)..

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## *Combined RF/Gradient Tests*

*Slice Thickness (cont.)*

- Method 2: Ramp Phantom (AAPM TG6)
- Phantom:
  - Crossed-ramp phantom filled with doped-$H_2O$ such that $T_1 \leq 200$ms. (Crossed-ramps correct for having a tilted or rotated phantom placement in the scanner.) Use $TR \geq 3T_1$.
  - It is a good idea to have 2-sets of crossed ramps in each scan plane. 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 $(ab)^{1/2}$. Can average over the two ramp sets.

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## *Combined RF/Gradient Tests*

*Slice Thickness (cont.)*

- Method 2: Ramp Phantom (AAPM TG6) (cont.)
- Advantage: No special pulse sequence required.
- Disadvantages: 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 means more averaging (and time).
- 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 (AAPM): ±1mm for >5mm slices.

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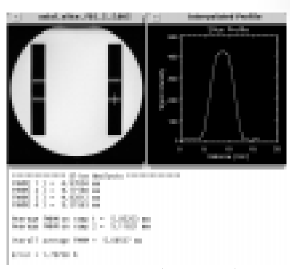
## *Combined RF/Gradient Tests*

Frequency-Encoding Direction →



Acquisition matrix:
512x256

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## *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 (AAPM): Disagreement <20% of the prescribed separation or ±1 mm, whichever is greater.

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## 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 (AAPM): Should agree with vendor's specified values. Problem: Vendor probably does not use similar means of determining SNR.

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## Global System Tests

*Signal-to-Noise Ratio (cont.)*

- AAPM suggested measurement is the NEMA approach.
- Phantom: Uniform doped-$H_2O$ sphere or cylinder.
- Acquisition: Two images of same location using *identical* acquisition parameters taken no more than 5 min apart. Repeat for all planes.
- Analysis: Subtract the images, use an ROI that encompasses 75% of the phantom, and compute $SNR=2^{1/2} \langle S \rangle / \sigma$, where $\langle S \rangle$ is the mean signal in either of the acquired images and $\sigma$ is the standard deviation in the difference image.

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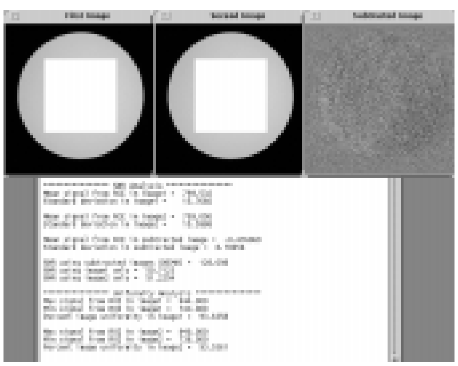

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## Global System Tests

*Percent Image Uniformity*

- Affected by $B_0$ inhomogeneities, $B_1$ inhomogeneities, eddy currents, and gradient uniformity.
- Phantom: Uniform phantom used for SNR tests.
- Acquisition: With phantom occupying ≥80% of FOV, use SE sequence with TR/TE=1000/30ms, and ≤10 mm slice thickness. Repeat for all planes.
- Analysis: Use ROI enclosing ≥75% of image and compute $PIU = [1 - (S_{max} - S_{min})/(S_{max} + S_{min})] \cdot 100\%$.
- Criteria (AAPM): Typical values >80%.

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## *Global System Tests*

- *High Contrast Spatial Resolution*
  - Most commonly assessed with a phantom containing successively smaller high contrast objects.
  - Criteria (AAPM): Should be able to resolve object sizes that are at least one (theoretical) pixel width in size.
- *Low Contrast Resolution*
  - Not discussed in either AAPM document. However, the ACR accreditation phantom does have a low contrast resolution section (4 disks of varying thickness with varying diameter holes).
  - Typically subjective evaluation, no known acceptance specs.

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## *Echo-Planar Imaging Tests*

- Echo-Planar Imaging (EPI) is the most widely utilized sequence for obtaining MR images extremely rapidly (down to 50ms/image).
- There are no established guidelines for EPI acceptance tests.
- In "snapshot 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 (75-250kHz, typically analog).
- Phase-errors, due to gradient instability or magnetic field inhomogeneities (including susceptibility effects), can cause geometric distortions that worsen with increasing sampling time and TE (particularly gradient-echo EPI scans).

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## *Echo-Planar Imaging Tests*

*EPI Acceptance Tests*

- Similar tests performed for "conventional" pulse sequences can be repeated for EPI, including linearity and geometric distortion, SNR, and PIU.
- 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. If the SGR is low, and/or a time-varying function, fMRI studies can be difficult.

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## *Echo-Planar Imaging Tests*

*EPI Acceptance Tests (cont.)*

- For EPI scanners, I currently assess:
  - Gradient linearity and geometric distortions for multishot and single-shot EPI.
  - Time variation of single-shot signal intensity, SNR, SGR, and PIU for ~5 min scan duration. (480 images, 6 slices for 80 timepoints)
- Also, on continuing basis, I check the time variations for each fMRI EPI protocol.
- With the current "explosion" in fMRI applications and widespread release of commercial single-shot EPI systems, acceptance testing and quality assurance need to be addressed.

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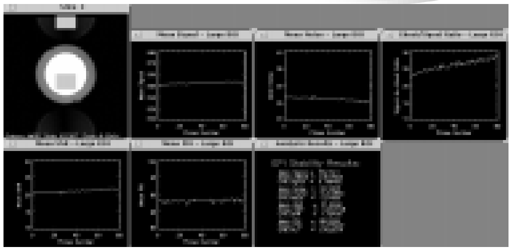
## *Echo-Planar Imaging Tests*



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## *MR Spectroscopy Tests*

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

- VOI location accuracy (SVT)
  - Acquire localized VOI images in several locations (isocenter and displacements in all three directions) and compare to prescribed locations.
- VOI localization quality (SVT)
  - Can minimally assess with VOI images.
  - Can assess more appropriately by evaluating spectrum from multicompartment phantom and looking for contamination of spectrum from regions outside VOI.

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## *MR Spectroscopy Tests*

- Automated shimming tests (SVT and SI)
  - Compare the quality of automated shimming parameters with manually-optimized parameters by measuring $H_2O$ linewidths. (Uniform phantom.)
- $H_2O$ suppression efficiency tests (SVT 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.
  - Compare automated $H_2O$ suppression parameters with manually-determined values.

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## *MR Spectroscopy Tests*

- SNR Tests (SVT and SI)
  - Obtain SNR measures from localized VOI in a uniform phantom.
  - On broadband systems, this might be done for all nuclei of interest, particularly $^{1}H$ and $^{31}P$.
- SI-Specific Tests
  - Assessment of spectral bleed from voxel-to-voxel in multicompartment phantom.

Note that some vendors are now producing MRS phantoms to be used for acceptance and QA tests.

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## *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
– Distance accuracy and geometric distortion
– SNR
– Image Uniformity

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