AAPM REPORT NO. 34

ACCEPTANCE TESTING OF MAGNETIC RESONANCE IMAGING SYSTEMS

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REPORT OF
TASK GROUP NO. 6
AAPM NUCLEAR MAGNETIC RESONANCE COMMITTEE

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Acceptance testing of magnetic resonance imaging systems: Report of AAPM Nuclear Magnetic Resonance Task Group No. 6[a)]

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AAPM NMR Task Group No. 6

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I. INTRODUCTION

The purpose of this document is to suggest and define elements that could constitute an Acceptance Test for magnetic resonance imaging (MRI) devices. The emphasis is on discussing the relevance, applicability, and performance of these elements as opposed to suggesting one comprehensive model for testing a generic MRI device. This approach is necessitated by the diversity of devices in the marketplace, as well as the availability of specific test equipment for the testing physicist.

The document lists individual tests, each with the rationale for the test, a proposed procedure, and suggested acceptance criteria. In several cases alternative procedures are proposed.

The earliest possible involvement of the physicist in the installation process is urged. Ideally, the physicist will be involved in the purchasing decision, construction meetings, and radiofrequency shielding tests. The setting of specifications and the review of the contract should be prime areas of consideration for the physicist. Involvement of the physicist at an early stage allows for much more input into the wording of the definitions and testing procedures for evaluating the specifications. The physicist should be able to participate in decisions such as determining the amount of emphasis to be given to clinical images in acceptance testing. The successful completion of a specific performance evaluation program should be the only basis for acceptance. Acceptance should not be conditioned on the first patient examination.

With an a priori knowledge of the system's capabilities and the test equipment available, tests can be defined for which both the physicist and the MRI system are equipped. These considerations are very important, for example, in deciding which of the suggested methods for measuring magnetic field homogeneity or eddy current compensation would be most appropriate.

Also at an early stage of the purchasing process, the physicist will be able to work with the vendor to establish which specifications are most important on a given system and how they should be tested. Many perfectly reasonable trade-offs are made during an MRI system's engineering design process. A classic example is the trade-off between signal-to-noise ratio (SNR) and image uniformity inherent to the design of a particular radiofrequency coil. The physicist must take these types of considerations into account when devising specifications appropriate to the individual system under consideration.

It is strongly recommended that the physicist work closely with the installation engineer. There is probably no one more knowledgeable about a particular unit than this individual. The engineer should know whether particular tests can be performed on the unit in question, and will also likely possess the proper equipment for performing them. The engineer may also suggest alternative methods oftesting specific parameters. Valuable time can be saved if the physicist is present to observe the vendor's acceptance procedures. These data can be included in the physicist's acceptance report. Acceptance testing is the determination of whether the system delivered is the system that was agreed upon by both the buyer and vendor and whether the system performs as specified.

The item or system that was mutually agreed upon should be defined and specified in a contract or sales agreement. Therefore, a vital first step is to review this document to determine exactly what has been promised. The physicist should obtain a copy of the final sales agreement and any supporting documents to which it refers. In some cases it will be beneficial to review the Operator's Manual as this often specifies particular performance parameters.

All items specified, such as coils, special acquisition support hardware (cardiac synchronization leads, for instance), and oxygen monitors should be identified. Similarly, all specified parameter values should be identified. These may include specifications of homogeneity or SNR.

Software features should be noted. These could include acquisition parameters such as pulsing times, number of slices, number of echoes, matrix sizes, etc. Processing features such as distance measurements, region-of-interest (ROI) manipulation and magnification should also be investigated.

II. PHANTOMS

The physicist is encouraged to review the report of AAPM NMR Task Group #1 on MRI quality assurance methods for a discussion of phantoms appropriate for use in testing MRI units.[1] Additionally, the vendors usually have their own specific phantoms. Some of these may even be provided to the site as part of the purchase agreement. If desired, the physicist can use the vendor's phantoms in testing the system. This procedure can reduce discrepancies between the physicist's and the vendor's test results since the vendor is familiar with the phantoms supplied with the system and has established specifications based on their use.

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Most of the tests described in this document can be performed using a sphere filled with solution. The spherical shape is recommended for reasons of symmetry. The container itself can be constructed of any nonsignal producing substance such as glass, plastic, or rubber.

Phantom solutions should have a relatively short longitudinal relaxation time constant *(T_1)*, 100-1200 ms, and a transverse relaxation time constant *(T_2)* similar to the longer values found in the body, 50-400 ms. For certain tests the phantom should mimic the loading effect of a human body on the radiofrequency circuit and the filler should be conducting. Also note that some coils on modern systems require loading similar to human body parts in order to function normally. The values for typical conductivities of body tissues found in Table I were taken from Michaelson and Lin.[2]

Equivalent conductance data for aqueous solutions of common salts are well established.[3] The relationship between equivalent conductance (Σ), in $\Omega^{-1}\,cm^2\,equiv^{-1}$, and conductivity ($\sigma$), in S cm^{-1} (siemens per centimeter) is

$$\sigma = C\,\Sigma/1000, \quad (1)$$

where C is the concentration of solution in g equiv l^{-1}.

The following recipe is proposed for a possible phantom solution: 1 liter H_2O, 0.0616 gram equivalents of NaCl (3.6 g), and 0.0157 gram equivalents per liter of $CuSO_4$ (1.25 g of pure $CuSO_4$ or 1.955 g of $CuSO_4$*5H,O). The above solution has a conductivity of 0.008 S cm^{-1} which satisfactorily mimics the conductive properties of most tissues.

The copper sulfate is mainly used to shorten the relaxation times of the loading solution. The combination of these solutes results in a solution with a T_1 of less than 200 ms for field strengths normally encountered in MRI. The above solution is also compatible with the guidelines set forth in NEMA Standards Publication/No. MS1[4] and any solution that conforms with these guidelines should be adequate for the tests described in the present document.

Ill. PHYSICAL OBSERVATION

This is perhaps the simplest test to perform but one that is often overlooked. No special equipment is required.

TABLE I. Conductivities of body tissues at various frequencies.[2]

Tissue type	Conductivity (S m^{-1})	Frequency (MHz)
0.9% saline	1.67	100
Blood serum	1.17	100
Vitreous humor	1.60	100
Eye lens	0.40	50-100
Kidney	0.90	50
	1.00	100
Liver	0.55	50
	0.59	100
Lung	0.54	50
	0.71	100
Heart muscle	0.96	200

A. Procedure

Make a physical inventory to determine if all items identified in the Sales Agreement are present. The physicist should also determine that devices, such as the camera system, intercom, alarm buttons, or movement of the patient table, function properly.

B. Acceptance decision

Any specified item that is found to be missing or deficient must be brought to the attention of the appropriate personnel.

IV. RADIOFREQUENCY SHIELDING VERIFICATION

A. Definition

The radiofrequency environmental interference shield is an important part of the installation. The shield is designed to minimize noise in the MRI images.[5,6]

In most cases the vendor specifies the performance of the shield in terms of decibel attenuation at particular frequencies. Usually the vendor will not install the MRI system until the shield has been certified to meet these criteria. Often a "ground" test will also be prescribed for the shield. This test is to ensure that the shield is electrically isolated from the environment. The shield is usually tested by an independent agency specializing in radiofrequency technology and retained by the shield subcontractor or the site.

The test is performed by placing an antenna on one side of the shield and broadcasting signals of various frequencies through the shield. Attenuation of this signal is determined by comparing these values to reference signals obtained with no shield in place.

B. Procedure

1. Method 1. Self-testing

If the site possesses, or can obtain, the equipment required for testing radiofrequency shielding, the tests can be done at several stages during site installation, This equipment may include:

(1) A signal generator capable of producing signals in the appropriate frequency range. If the generator is not capable of producing signals of sufficient amplitude, considering an expected attenuation of 100 dB, an amplifier will be needed.

(2) Two antennas calibrated for the proper frequencies.

(3) A receiver, such as a spectrum analyzer, covering the entire range of frequencies with adequate sensitivity so that the combination of gain and sensitivity will permit attenuation measurements of the required limits.

The first test should be performed upon completion of the shield. This test is necessary to confirm that the shield meets the MRI vendor's attenuation requirements.

Another test should be performed after the vendor has installed the magnet. The vendor must penetrate the shield during installation to provide a passage for cables from the computer and power supplies to the magnet. Testing after magnet installation will demonstrate any loss in radiofrequency shielding integrity. Additional tests should be done

following the completion of the room and after installation of the total MRI system. These tests will demonstrate that the shielding integrity has been maintained through all phases of construction.

2. Method2. Independent contractor

Often an independent radiofrequency testing agency will be contracted to test the shielding integrity. Ideally the physicist should be present during the testing to confirm the procedure and results. The physicist should ensure that there are calibration seals on the testing equipment. A 20-dB attenuator may be used to check the accuracy of the equipment's calibration if there is any doubt.

If the physicist cannot be present during the testing, the results of the test should be reviewed and kept available for future reference. This review will be useful in the event that the integrity of the shield should come into question, or if an upgrade or system modification is performed. This document will verify that the shield was acceptable prior to any modification by the vendor.

C. Acceptance decision

Any measured attenuation less than specified should be brought to the attention of the site.

V. CRYOGEN CONSUMPTION

A. Definition

The rate at which cryogens are consumed may be specified by the manufacturer. Slight increases in this rate can result in substantial expenses.

B. Procedure

Determine the cryogen (liquid nitrogen and helium) consumption for a given period of time (the longer period of time the better). This determination can be done in a number of ways. Some sites will have a direct flowmeter and others will only indicate the fill level. In this case it will be necessary to monitor the time between refills and the amount used in refills in order to assess the average rate of consumption.

C. Acceptance decision

Consumption rates in excess of those specified must be brought to the attention of the site.

VI. RADIOFREQUENCY COILS

A. Tuning and matching

Radiofrequency coils fall into a class of circuits called "resonant" or "tank" circuits since they are capable of storing energy.[7,8] If the coils are not properly tuned and matched, usually to a 50Ω impedance, ineffective delivery of radiofrequency power, image intensity distortion, and reduced sensitivity of signal reception will result.[8,9]

Tuning and matching are done either automatically by the system or manually by the operator. Automatic tuning is performed totally by the machine and evaluation of its performance is largely qualitative. The procedure below is intended only for manual tuning and matching.

B. Tuning procedure

Position a phantom at the center of the coil to be tested. Both the head and body coils should be tested. For this test no images will be generated but the phantom should possess the loading characteristics similar to the human body for relevant results.

Use the manufacturer's procedure for tuning. The reflected radiofrequency power indicative of the degree of impedance matching at the resonance frequency should be displayed in some way. In essence, the less power reflected, the closer one is to a proper match. Adjust the tuning and matching capacitors to optimize the match. This test may be repeated for phantoms of different volumes.

C. Surface coils

Surface coils are used to obtain higher SNR in high resolution imaging protocols. They come in a variety of designs and configurations. This variety and the fact that each manufacturer specifies particular performance parameters differently make it problematic to develop blanket quantitative acceptance testing. Thus if quantitative testing is required the physicist should consult with the manufacturer regarding the proper testing procedures for a particular surface coil. For qualitative testing the physicist can perform a scan using each surface coil in several orientations. After observing the resulting images, the physicist should comment on any problems encountered with tuning or image quality.

VII. B_0 FIELD HOMOGENEITY

A. Definition

Homogeneity refers to the uniformity of the main magnetic field strength B_0 over a designated volume. It is usually specified in parts per million of the magnetic field strength over a spherical volume (d.s.v. = diameter of spherical volume). The actual homogeneity will be influenced by a variety of factors, including inhomogeneities in the B_0 field produced by inaccuracies in the coil windings, the degree to which B_0 is perturbed by external ferromagnetic structures and the degree to which the above influences can be compensated using magnetic fields produced by room temperature shim coils or passive shimming with pieces of steel. The shims are designated to eliminate unwanted harmonics of the field within the magnet.[9,10] Inhomogeneities can contribute to geometrical distortion of images, adversely influence image uniformity, and compromise the signal-to-noise ratio (SNR) in some fast imaging sequences.

B. Procedures

1. Method 1. Magnetic field probe

The installation engineer measures the magnetic field homogeneity with data taken from a custom designed radiofrequency probe which accurately positions a small water (proton) sample at various points within the magnet. If possible,

the physicist should be present during these measurements and use the results obtained by the engineer as demonstration of the B_0 field homogeneity.

2. Method 2. Spectral peak

Position a uniform, spherical phantom at the "isocenter" of the magnet using the patient positioning system. The phantom should have a spherical volume diameter similar to that specified by the manufacturer. Produce a spectrum from the sample. Make sure that the frequency resolution is much less than the expected peak width. Measure the full width at half maximum (FWHM) of the spectral peak. Convert the FWHM from Hz to ppm of the B_0 field strength using the Larmor equation,[7,9]

$$\text{FWHM (ppm)} = \text{FWHM(Hz)}/42.576\, B_0(T).$$

The FWHM (ppm) defines the inhomogeneity over the phantom volume.

3. Method 3. Phase difference map

This test offers an accurate measurement of B_0 homogeneity using a uniformity phantom. However, the test requires features of the MRI system (e.g., display of phase images) which may not be available on all units. The effects of gradient nonlinearities and B_0 inhomogeneities can be separated by mapping the B_0 field strength. If the MRI system can perform image subtraction and display phase images, a pixel-by-pixel measurement of field inhomogeneity can be obtained."

Position the phantom in the center of the body coil. The phantom should enclose, at least, a 10-cm-diam circle, or 85% of the area specified in the contract, whichever is larger.

Employ a simple, spoiled gradient echo sequence. The use of a radiofrequency spin echo would result in rephasing of the phase differences due to field inhomogeneities. Acquire an image using a moderate TE of about 30-40 ms (TE_1) and display this image as a phase map. Acquire another image using a TE only a few ms longer than TE_1 (TE_2). Subtract the second image from the first to obtain an image in which each pixel intensity represents the phase difference between the two acquisitions, since the T_2 of the solution is the same throughout.

The difference $(d B_0)$ between the B_0 field at a given voxel and the reference value at the center of the field of view (FOV) is

$$d B_0 = df/g\ (TE_1 - TE_2),$$

where the $d B_0$ is in mT, df is the phase difference in radians, g is the gyromagnetic ratio expressed as 42 576 Hz mT^{-1} and the TE values are in units of seconds. This procedure can be repeated to obtain data from all applicable planes.

Determine the greatest difference in any plane between the values of $d B_0$ within circular regions of interest having the specified diameters (d.s.v.). This value divided by the B_0 field strength of the magnet will yield the homogeneity (in ppm) for the specified d.s.v. It may be noted that poor eddy current compensation may also influence phase images.

C. Acceptance decision

The homogeneity is usually specified by the manufacturer. The values obtained should be compared to those specified. Typical values are around 10 ppm over a 30 to 40-cm-diameter sphere, for superconducting magnets.

VIII. GRADIENT FIELD STRENGTH

A. Definition

Gradients are used to encode spatial information. This is done by making either the frequency or the phase of the MR signal spatially dependent. Errors in the gradients affect the slice thickness, position of slices, and the shape of structures within the field of view.

B. Procedures

The following test checks the strength of the readout gradient. To check all three gradients, the orientation of the phantom can be changed appropriately and separate images acquired. While performing the test described below, employ scan parameters that will test the limits of the gradient strength, such as the largest spectral width or smallest FOV allowed.

Observe the image of a uniformity phantom of known diameter *(d).* Measure the frequency range across the image in the readout direction. On many systems the frequency cannot be measured directly. In this case, the indicated distance in meters must be converted to frequency in Hz. An FOV that is appropriately larger than the dimensions of the phantom should be selected. The image of the phantom is used to verify the size of the FOV. From the size of the FOV, the Hz m^{-1} can be calculated as the spectral width (SW) divided by the FOV. If the spectral width is not known, it can be determined, for systems using quadrature detection, with the equation[7,12,13]

$$\text{SW(Hz)} = N/t_a,$$

where N is the matrix size in the frequency encoding direction and t_a is the acquisition time; that is, the total time during which the data can be digitized.

The read-out gradient strength (G,), in mT m^{-1}, will be

$$G_r = \text{SW} / g\, d.$$

One must be careful to determine the true value of N since some systems will oversample in the signal (i.e., digitizing 512 points but displaying only 256).[14]

C. Acceptance decision

The maximum gradient strength measured should be that specified by the manufacturer. Note that often vendors may specify gradient field strengths as the maximum that can theoretically be produced with the system's gradient amplifiers and not as the maximum gradient strength available on the current version of software.

IX. EVALUATION OF EDDY CURRENTS

A. Definition

Eddy currents are induced in nearby conducting structures by the changing magnetic fields that are established in the gradient coils. Eddy currents produce transient magnetic fields that oppose the gradient fields. Inadequate eddy current compensation can produce various image artifacts and also reduce the SNR. The presence of eddy currents can be evaluated using pulse sequences in which only one of the three gradient coils is activated. This will allow for the determination of the contribution to the eddy currents from each gradient coi1.[15,16]

B. Procedures

1. Method 1. Integrator circuit

The installation engineer may evaluate the gradient waveforms through the use of an instrument especially designed for the visualization of the currents produced in the gradient coils. If at all possible, the physicist should be present during the test so that characteristics of gradient pulses which are commonly specified, such as rise and fall times, may be verified.

Most often, a pickup coil consisting of many turns of wire, is placed slightly away from center in the direction of the gradient coil which is to be evaluated. The changing electrical current in the gradient coil during the gradient pulse will induce voltage in the pickup coil. The voltage induced in the pickup coil is input to an integrator circuit and then viewed on an oscilloscope or other video display. The true shape of the gradient pulse in the coils is shown on the display.

2. Method 2. Effect on signal from sample

This test can be performed in addition to, or in place of direct investigation of the gradient waveforms. It is a means of evaluating eddy currents for physicists who cannot be present during the installation engineer testing. A detailed procedure for eddy current analysis using this method has been described elsewhere."

Using a uniform phantom, employ a pulse sequence with a gradient pulse of between 5-20 ms. This pulse amplitude should be that specified in the definition of minimum rise time. After a delay *(D)* of 100 ms, apply a radiofrequency pulse. Observe the free induction decay (FID) signal, and record its integral. Repeat the above three steps, decreasing *D.* The procedure should be repeated until the *D* is down to 1 to 2 ms. A decrease in the integral of the observed FID shape indicates that eddy currents are beginning to effect the signal. The measurement is repeated for each of the three gradient coil sets. If it is desireable, one may observe changes in the lineshape of the transformed FID as *D* is decreased.

C. Acceptance decision

For method 1, each pulse should be close to rectangular in shape. The rise and fall times should meet the manufacturer's specifications. For method 2, the FID should remain constant until $D \leq 3$ ms.

X. RADIOFREQUENCY CALIBRATION

A. Definition

The MR system uses control files to generate all the pulses used in the imaging protocols. It is very important that all those files are properly calibrated, so that the nominal nutation, or tip, angles delivered by the radiofrequency pulses generated from them are in constant, proper relationship during different scanning conditions. The radiofrequency matching and tuning and the transmitter and receiver amplifier levels are set up prior to scanning to ensure that the proper conditions are established for the scanning protocol chosen. However, the setup routine does not ensure that the control files themselves are accurately calibrated. Improperly calibrated files can result in a variety of image artifacts.

B. Procedure

Determine if the system is equipped with calibration routines or similar diagnostics. If so, they can be used to determine proper calibration. The test can be done with a uniformity or other appropriate phantom. Employ spin echo protocols that cover the full range of those recommended for clinical use on the scanner. The minimum slice gap should be used.

Observe the images for artifacts such as ring patterns, central zipper artifacts, or off-center ghost images. Their presence may indicate miscalibration of the radiofrequency control files.

For gradient echo protocols such as FLASH, GRASS, FISP, etc., use the following procedure.

(1) Run a typical clinical gradient echo sequence, setting the radiofrequency power to produce a small nutation (e.g., 10° tip angle).

(2) Measure the signal intensity from the central region of interest. Record the intensity, power level, and the nutation angle used.

(3) Repeat steps 1 and 2 for images obtained with a range of nutation angles (for example 10°-200°). A plot of signal intensity versus power level should show a sinusoidal pattern. The signal varies with the size of the nutation angle, the maximum at 90°, zero at 180°, and going more negative until it reaches 270°. The nutation angle should change linearly with the square root of the applied power.

(4) Observe images obtained for patterns of high intensity lines, parallel to the phase-encoding direction, with the brightest line in the center. Such lines suggest that "spoiler" or rephasing gradients are not properly implemented.

C. Acceptance decision

Comment on any artifacts observed. In most cases the installation engineer will be able to resolve any significant problems on site.

XI. QUALITY OF THE RADIOFREQUENCY OUTPUT

A. Definition

The rf pulses used in MRI are generated using a stable radiofrequency source (radiofrequency synthesizer) which

usually works in the coherent (phase locked) mode to assure stability of the generated signal.[8,9] Multislice protocols require rapid switching of the radiofrequency offset; commonly the coherence of the synthesized signal can be restored within several μs after switching. This feature, combined with high stability of the generated frequency (commonly 10^{-8} ppm or better) is more than sufficient for most standard MRI applications. The radiofrequency signal is then modulated (most often in amplitude, but frequency and/or phase modulations can be found as well) to generate the appropriate pulses. Radiofrequency output which is "deficient" in quality can result in a variety of imaging artifacts depending on the magnitude and type of the defect.

B. Procedure

1. Method 1. Superconducting systems

Position a uniform phantom at isocenter, and select a pulse sequence in which only slice-select gradients and radiofrequency pulses are used. Observe the FID signal using a TR of 1000 ms. On certain units, the signal will be displayed directly on the viewing monitor. In others it might be necessary to connect an oscilloscope to the unit. The site engineer should be consulted for the proper connection location.

With the control frequency as close to resonance as possible, observe repeated FIDs. There should be little fluctuation in the patterns. Figure 1 shows a marked drift observed for two consecutive FID signals in the real channel, which can be due to either phase or frequency drift.

Figure 2 shows a frequency drift, equal to the offset of the frequency from the resonance condition. Any large changes in the amplitudes collected in consecutive phase encoding cycles indicate phase instability (Fig. 3). It is important that TR > 5 T_1 of the phantom, otherwise the residual magnetization will introduce signal fluctuations and invalidate the observations.

2. Method 2. Resistive systems

In resistive systems, instabilities caused by fluctuations of the main magnetic field will add to the observed effects, masking problems caused by the radiofrequency hardware.[18] In these cases, the radiofrequency channel should be evaluated using an oscilloscope and coupler, and looking at the following test points in order:

(a) On the transmitter side, check the rf pulses after modulation and before amplification. Obvious distortions in the shape of the signal indicate a problem with the modification.

(b) Check the output of the rf amplifier. *Caution:* never connect your scope directly to the output of the rf amplifier. Place an appropriate attenuator in line to avoid serious damage to the scope.

(c) On the receiver side, check the rf signal to the demodulator, and the reference rf signal to the quadrature detectors. This signal should be a "clean" sinusoidal curve with low noise.

(d) Phase stability can be evaluated by connecting the x-y display of the scope to the output the real and imaginary

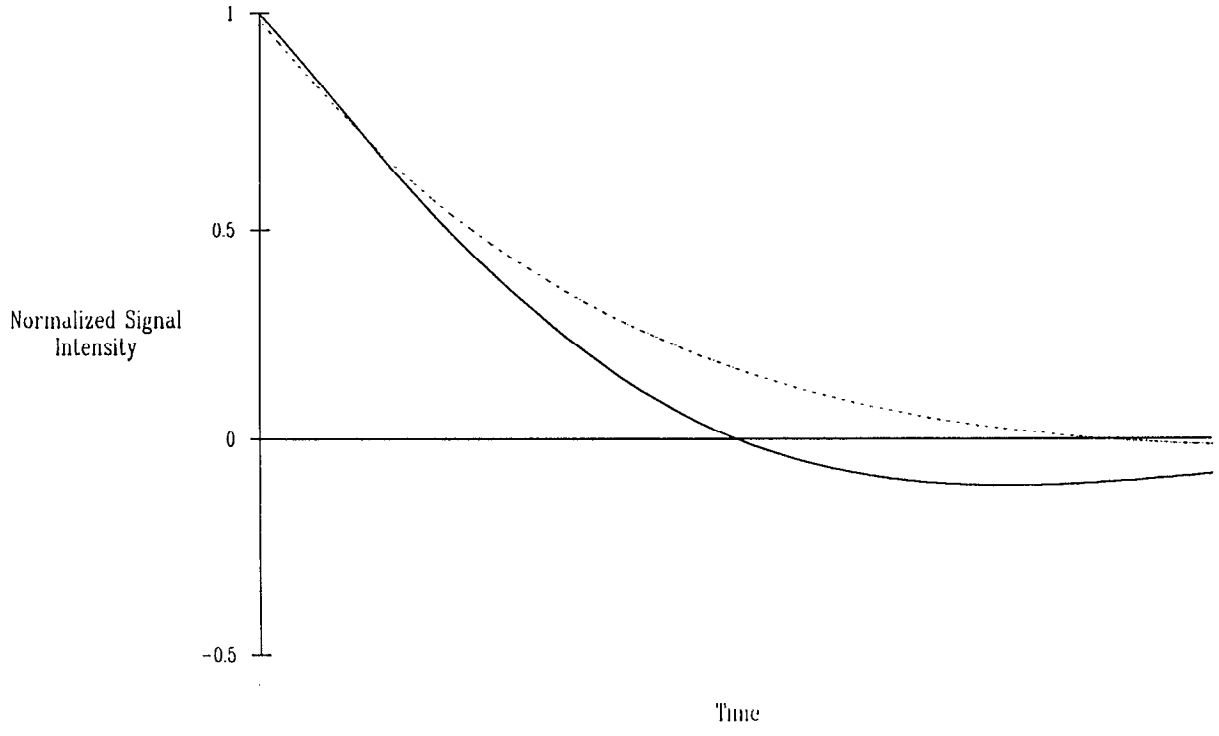

FIG. 1. Two consecutive acquisitions of the real channel FID signals. The shift in the position of the time axis crossing indicates a small temporal instability that can be caused by the drift in either the frequency or the phase of the signal. This is an easy and reliable check of the overall stability of the radiofrequency and magnet subsystems.

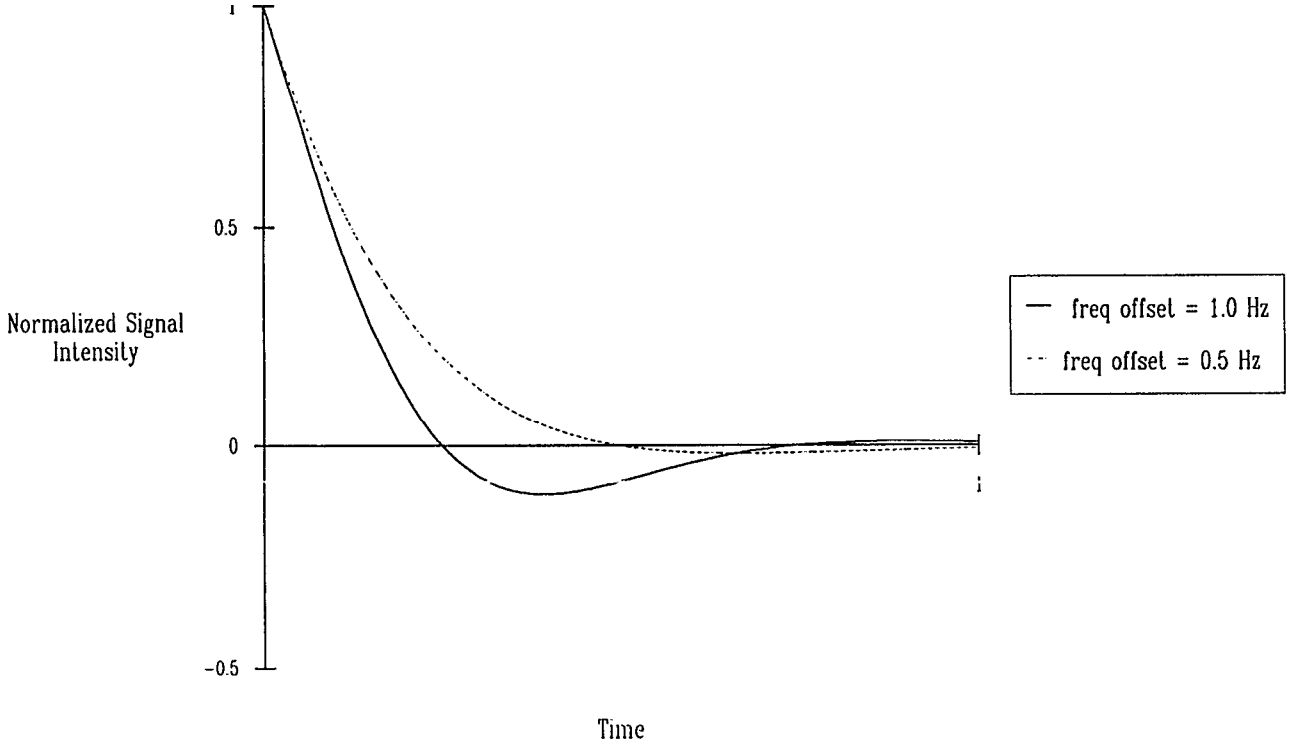

FIG. 2. Two consecutive FID signals, slightly off resonance, displayed on the "real" channel. Frequency drift is indicated by the difference betweenx-intercept values.

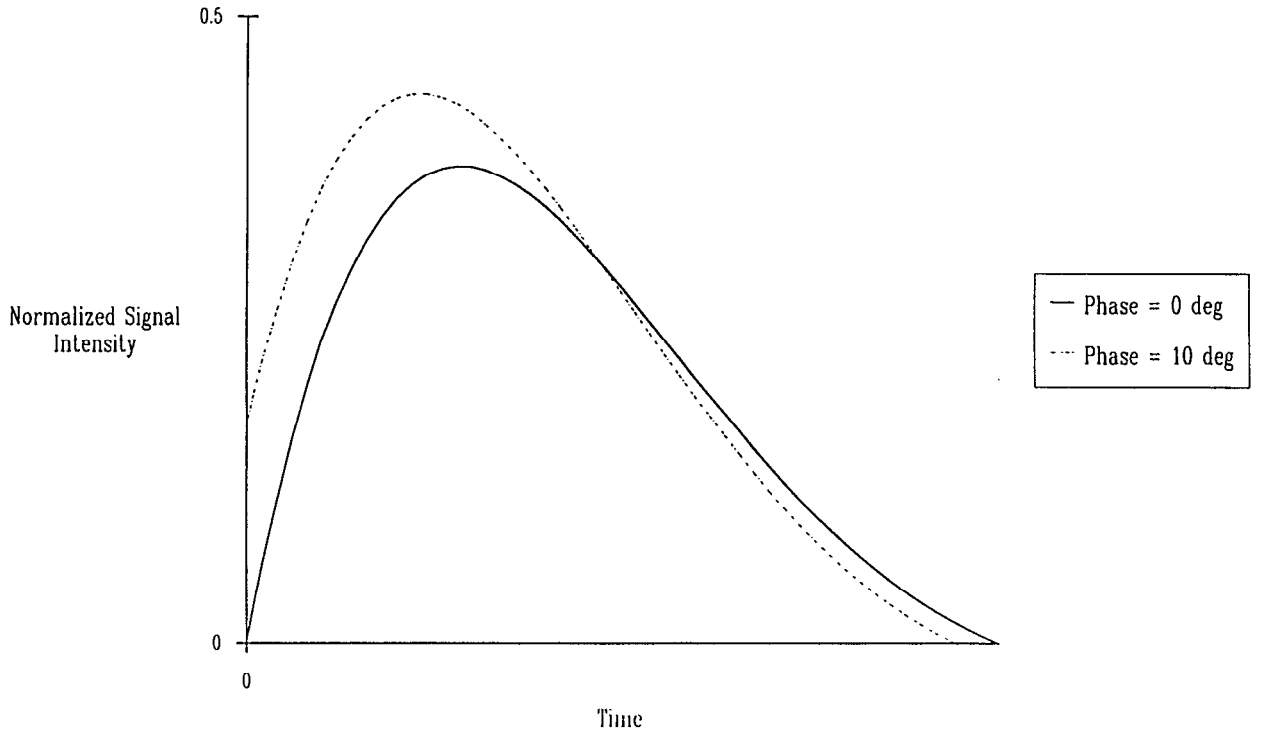

FIG. 3. Two consecutive FID signals set slightly off resonance as displayed on the "imaginary" channel. Phase drift is indicated by the difference in intensity at $t = 0$.

channels. The stability of the resulting Lissajoux pattern is indicative of phase and frequency stabilities.

C. Acceptance decision

For superconducting systems fluctuations in FID or echo signal should be less than 2% when using TRs > 3 T_1 of the phantom solution. For resistive units, report any distortions observed in the signal to the site engineer.

XII. QUADRATURE PHASE DETECTION

A. Definition

Quadrature phase detection is used primarily to increase the signal to noise ratio.[7,9,19] It involves the use of two phase sensitive detectors, tuned to a reference signal 90° apart in phase (quadrature). Signals from the coil are analyzed by receiver channels using these phase shifted signals. If the receiver channels are not set correctly, i.e., the phase difference is not 90°, a ghost artifact may occur. The ghost image will be rotated 180° about the center, as compared to the primary image.[20]

B. Procedure

Place a phantom in one quadrant of the field-of-view and offset in the imaging plane from the magnet's isocenter. Employ a multislice, multiecho pulse sequence. Inspect the images for quadrature ghosts. For each ghost, measure the signal from a central ROI. Similarly, measure the signal for the primary image.

Note that these images provide the opportunity to discern other system defects. Ghosts due to stimulated echoes will appear in the same quadrant as the phantom but in a second or third echo. Search the images for a single bright pixel at the center of the images. This may indicate dc offset, or residual voltage present at the detector's output without any signal at the input.

C. Acceptance decision

The signal from a ghost artifact should be less than 2% of the signal from the phantom, or should meet the manufacturer's specifications. Comment if dc offset is suspected.

XIII. SIGNAL-TO-NOISE RATIO

A. Definition

System signal-to-noise ratio (SNR) is an important determinant of the detectability of small, low contrast lesions. It is recommended to obtain an initial characterization of the SNR at the time of acceptance.[1,4]

B. Procedure

A uniform phantom should be used. The phantom should enclose at least 85% of the specification area, but should not be smaller than 10 cm in diameter for head scans and 20 cm in diameter for body scans. The signal producing volume should have a T 1 between 100 and 1200 ms, and a T 2 between 50 and 400 ms.[1] The spin density should be close to that of H_2O (±2%).

Scan parameters should be adjusted so that TR is less than or equal to 5 T_1 and TE is set to a routine clinical setting. Use a single slice, single echo protocol with a slice thickness of 10 mm. The FOV should be less than 110% of the largest dimension of the rf coil.

Perform the standard clinical prescan calibration procedure. Execute two scans sequentially, with less than 5 min elapsed time from the end of the first scan to the beginning of the second.

Determine the mean pixel value from a centrally positioned region-of-interest (ROI) on the image. Label this value *"S"*. The ROI must include 75% of the image of the phantom. Calculate the pixel-by-pixel difference image:

image 1 - image 2 = image 3.

Using an ROI identical to that used in determining the mean signal *S*, determine the standard deviation of that area for image 3. Call this value "N". The SNR is calculated as follows:

$$\text{SNR} = \sqrt{2}\,(S/N).$$

C. Acceptance decision

Measured SNR figures can be compared to those specified by the manufacturer. SNR figures should be comparable for all orientations when the same pulse sequence, rf coil, and phantom are used. Note that the procedure above refers only to single slice, single echo scans. The physicist may find it desirable to perform this test with other parameters, such as multislice echo, or difference slice thicknesses.

XIV. IMAGE UNIFORMITY

A. Definition

Image uniformity refers to the ability of an MRI system to depict similar regions with the same intensity in a homogeneous volume. Nonuniformity may be the result of radiofrequency or magnetic field inhomogeneities, eddy currents, radiofrequency coil geometry or penetration, of inadequate gradient pulse calibration. For a more complete description of image uniformity testing, see the report of AAPM NMR Task Group #1.[1]

B. Procedure

Any homogeneous phantom can be used. The phantom should encompass about 80% of the FOV. The filler material should have a conductivity close to that of tissue. Employ a pulse sequence with the following parameters: TR = 1000 ms, TE = 30 ms, single echo, slice thickness = 10 mm or less.

Center an ROI on the image of the signal producing volume, enclosing at least 75% of the image, but excluding regions near the edge. Determine the maximum (S_{max}) and minimum (S_{min}) pixel values within the ROI. Calculate the percent integral uniformity (PIU),

$$\text{PIU} = [1 - (S_{max} - S_{min}) / (S_{max} + S_{min})] \times 100\%.$$

Repeat the above measurements and calculations for all orientations.

C. Acceptance decision

This parameter should meet the specifications of the manufacturer. Note that image uniformity is inherently less in higher field systems due to radiofrequency attenuation effects. Typical uniformity values exceed 80%.[1]

XV. IMAGE LINEARITY (GEOMETRICAL DISTORTION)

A. Definition

Geometric distortion refers to the ability of the MRI system to reproduce the dimensions of an object. Improper linearity will result in distortion of the image.' The spatial linearity of the MR image will be influenced by the B_0 field homogeneity, the calibration of the gradient pulses, and linearity of the gradient fields.

B. Procedure

Use a uniform phantom which is either square or circular and obtain a spin echo image of the phantom. Ideally the dimensions of this phantom are similar to the d.s.v. specified by the manufacturer. Using the distance measurement software, measure linear distances on the image. For circular images, measure several diameters. For square images measure the two diagonals, as well as the length and width of the image. Some linearity phantoms consist of an array of rods or holes. Distances between these objects can also be used for determining geometrical distortion.

The geometric distortion (GD) is defined by the equation

$$\mathrm{GD} = \left(\frac{D_{\mathrm{true}} - D_{\mathrm{meas}}}{D_{\mathrm{true}}}\right) \times 100\%,$$

where D_{meas} is the distance measured in the image and D_{true} is the corresponding physical dimension of the phantom. Note that in some systems the absolute size of the image may vary with distance from the center of the acquired volume in multislice acquisitions. Thus the test should be repeated for several slices.

C. Acceptance decision

Measured geometric distortion figures should be as good or better than the manufacturer's specifications. GD should not exceed 5%. Typical values are less than 2%.

XVI. SLICE THICKNESS

A. Definition

Slice thickness is an important parameter in MRI. Partial volume effects can significantly alter sensitivity and specificity. Quantitative measurements such as T_1 and T_2, are also greatly influenced by slice thickness. Inaccuracies in slice thickness may result in interslice interference in multislice acquisitions, and invalid SNR measurements.

B. Procedures

1. Method 1. Frequency profile measurement

Any uniform phantom can be used with the pulse sequence displayed in Fig. 4 to obtain a frequency profile of the selected slice. No phase-encoding gradient is necessary. The same gradient that is used for slice selection is used as the read-out gradient. Determine the slice thickness by measuring the width of the frequency profile and converting it to distance.

A two-dimensional image of the edge of the slice can be produced by adding a phase-encoding gradient to the sequence discussed above. This approach may be useful for evaluating the spatial variation of the thickness of the slice.

2. Method 2. Phantom method

There are a variety of phantoms designed to evaluate slice thickness. All are some variation of an inclined surface. These may include wedges, ramps, spirals, or steps. The surface of the plane forms an angle (f) with the scan plane. Slice thickness must be considered in determining this angle, as well as the pixel dimensions (d). At least six pixels must be provided across the full width at half maximum (FWHM) of the slice profile,

$$\tan f \leq \mathrm{FWHM} / 6\, d.$$

Any imaging sequence can be used provided that TR > 3 T_1 of the image producing material, and the highest pixel resolution is provided.

The slice profile (SP) is obtained by plotting pixel intensity along a dimension orthogonal to the ramp width. Find the maximum value of the SP, interpolating if necessary. The FWHM is the width of the SP at one-half of the maximum value. The slice thickness is FWHM times tan f.

Slice thickness measurements are very sensitive to errors of tilt, or rotation along they axis. These errors can be corrected by using inclined surfaces oriented at fixed angle (f) with respect to one another. In this case, the SP should be obtained of each surface. The FWHM then becomes

$$\mathrm{FWHM} = \frac{(a+b)\cos\phi + [(a+b)^2\cos^2\phi + 4ab\sin^2\phi]^{1/2}}{2\sin\phi}, \quad (2)$$

where a and b are the measured FWHM of the two SPs. Note that for f = 90° then Eq. (2) is simplified to, FWHM = $\sqrt{ab}$.

Slice thickness may vary with distance from the center of the imaged volume, with multislice acquisitions. It may be advisable to repeat the tests described above for a multislice sequence.

C. Acceptance decision

Measured slice thickness should meet the manufacturer's specifications.

XVII. STABILITY OF THE MAGNETIC FIELD

A. Definition

Drifting of the magnetic field can affect both SNR and image resolution. In superconducting magnets this would be due to a slow B_0 field decay. Resistive magnets may have significant field drift soon after they are energized, but this should stabilize within several hours. For a detailed descrip-

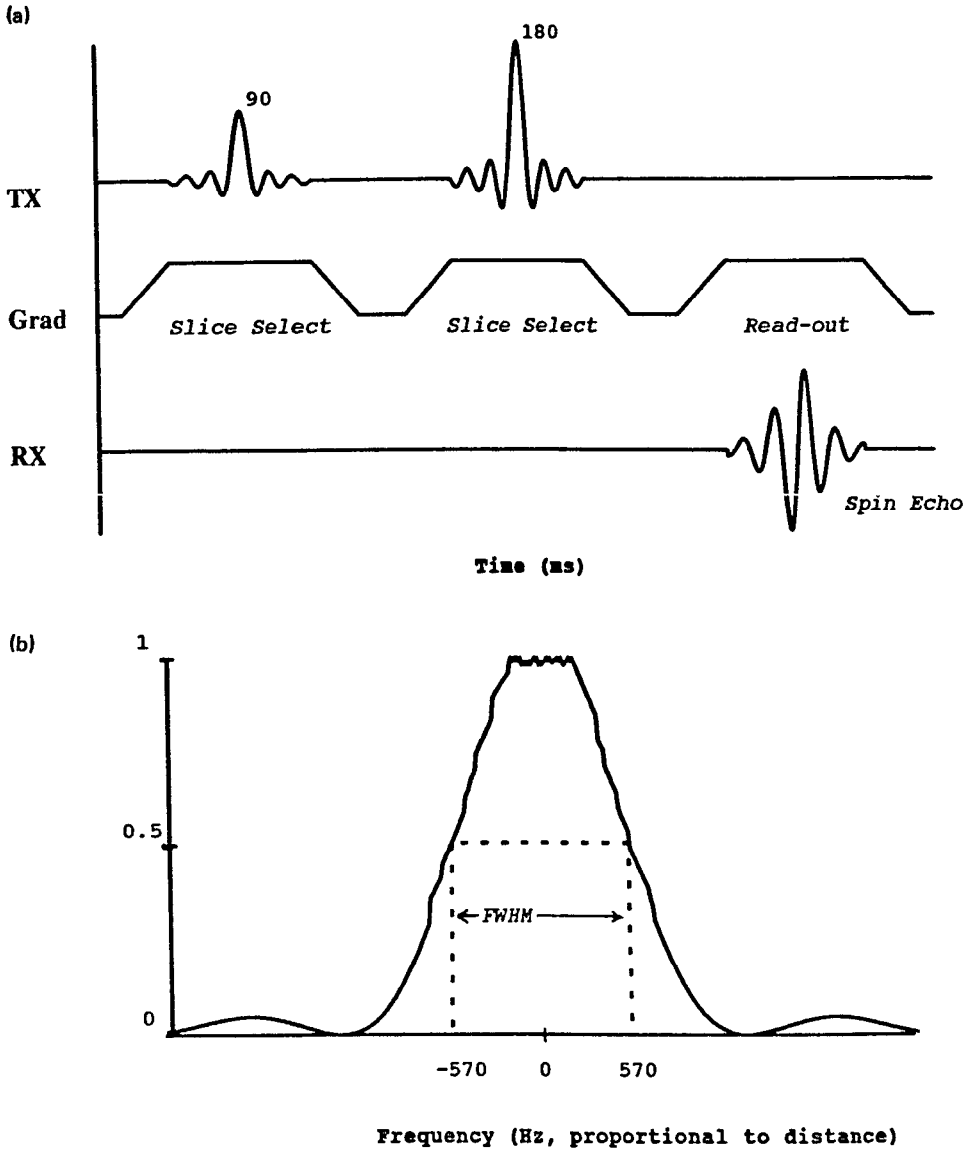

FIG. 4. Sample pulse sequence for obtaining slice profile. (a) Pulse sequence diagram. (b) 1DFT profile resulting from spin echo produced by pulse sequence in (a).

tion of stability testing on resistive magnets, see Slone and Fitzsimmons.[18]

B. Procedures

1. Method 1. Superconducting magnets

Position a small uniform phantom at the isocenter of the head coil. Produce a spectrum, recording the time of acquisition and central frequency for this spectrum. Acquire another spectrum 8-12 h later and record the same data. Obtain the difference, in ppm, between the central frequencies of the two peaks, and divide by the time between the measurements.

2. Method 2. Resistive magnets

Position a small uniform phantom in the center of the head coil. Employ a pulse sequence that will produce a spectrum. Record the central frequency and time of scan. Perform and record an SNR measurement. Repeat this measurement regularly for 8 h after the system is energized.

Determine the FWHM of the spectrum produced by a single scan ($FWHM_s$). Repeat the pulse sequence described above for a period of five minutes, adding all of the scans together. Determine the FWHM of the multiple acquisition ($FWHM_m$).

$$\text{stability (Hz or ppm)} = FWHM_m - FWHM_s.$$

C. Acceptance decision

For superconducting magnets, the decay rate should not exceed 3 ppm/day (0.125 ppm/h), or as specified. For resistive magnets, short term fluctuations are typically within 2-10 ppm. Comparison of the SNR measurements will show when magnetic field drift affects image quality.

XVIII. IMAGE ACQUISITION SOFTWARE

A. Definition

The MRI unit acquires images based on a complex set of instructions entered by the operator that concern the number of slices, echoes, and acquisitions, as well as the FOV, matrix size, and pulse times. These parameters are in addition to a variety of special "accessory" treatments that might involve software applications, or particular hardware. All of the above parameters will have a decided effect on the quality of the final image.[21-23]

B. Procedures

For each specific parameter, determine that values specified can be achieved. In many cases it will not be necessary to actually initiate a scan, as the software may indicate whether values entered by an operator can be obtained. At some sites, specifications for individual parameters will not be given. In these instances, the agreement will probably indicate that a particular software version, or package, will be provided.

It is impractical to evaluate all the parameters of the software package in order to determine if it is applicable. One option is to be present when the software package is tested by the engineer or applications specialist who will probably have access to "diagnostic" programs that may be used to evaluate the operation of the software. Another option is to contact the vendor and determine how the testing will be done, and, if applicable, request the information necessary to conduct the diagnostic evaluation.

XIX. IMAGE PROCESSING SOFTWARE

A. Definition

The image processing software should be evaluated to ensure that the site received the proper software, and that it functions adequately. Software features will vary from site to site, and vendor to vendor.

B. Procedure

Refer to the Operator's Manual to use as a guide to testing the inclusion and operation of each function. Indicate the presence or absence of each function and a qualitative description of its performance. Evaluate the speed with which images are retrieved from files and the ease of operation of the filing system.

The operation of the hardcopy device should be evaluated at this time also. Make hard copies of images and note geometric distortions and nonuniformities which were not apparent on the video display. Look for phosphor defects. Comparisons of images of the SMPTE Test Pattern are recommended.[24] (See the Appendix.)

C. Acceptance decision

Certify whether or not the image processing software has all of the functionality specified by the manufacturer. Comment on any difficulties encountered or deficiencies observed.

XX. SPECIAL/OPTIONAL ACQUISITIONS

A. Definition

Each special acquisition or function specified in the sales agreement should be tested to determine proper operation. Examples might include: spectroscopy, 3DFT imaging sequences, cardiac or respiratory gated acquisition, flow sensitive imaging, or rapid imaging sequences.

B. Procedures

Some of these features may be experimental options that will have poorly defined capabilities at the time the contract is signed. However, the following are examples of tests that can be performed.

Special equipment such as the EKG system and spectroscopy surface coils must be present and in working condition. EKG leads, in particular, may be specified to meet certain safety requirements with regard to ground currents, and these conditions should be verified. The EKG leads and the entire cardiac package should be shown to perform as specified by obtaining gated heart images from volunteers. Verification may involve obtaining gated images from humans and comparing them with nongated images. Human images and/or images of specially designed flow phantoms may be necessary to document the effectiveness of flow sensitive imaging protocols.

The radiofrequency, gradient, and image quality tests, as outlined above, can be employed on multichannel systems for protocols at each resonant frequency to ensure the proper calibration of the radiofrequency system, gradient pulses, etc. for spectroscopic or chemical shift imaging protocols.

C. Acceptance decision

Comment on any deficiencies observed.

XXI. ACOUSTIC NOISE MEASUREMENT

A. Definition

The oscillating currents driving the gradient coils produce vibrations that are usually audible to the patient. The loudest noise will occur with pulse sequences using high gradient current amplitudes and duty cycles.

B. Procedure

An integrating sound level meter (ISLM) which meets ANSI standard SI.4-1983, Type 0 or 1, or IEC651 Type 0 or 1 is used to measure the sound pressure level (SPL).[25] The microphone used must be omnidirectional and insensitive to magnetic fields, or calibrated to account for the magnetic field. An extension cable is also required.

Calibrate the ISLM according to instructions. Position the microphone at the magnet isocenter, orthogonal to the patent axis, approximately where the patient's ear would be. Place the ISLM outside the 10 gauss line.

An A-weighted SPL frequency corresponds to noise levels similar to those heard by the human ear. Measure the ambient A-weighted root-mean-square SPL (L_{eq}). Set the detector to root-mean-square (rms), frequency weighting to

A-weighted, and the measurement period to ≥20 s. Time weighting may be fast or slow. The MRI system is on but not scanning during this measurement.

Select a protocol from each major sequence type that has many gradient current transitions per unit time (e.g., minimum TR and TE for field echo acquisitions, maximum number of slices for spin echo acquisitions) and large gradient current amplitudes (minimum slice thickness, minimum FOV, minimum rise time).

Initiate the sequence. Measure the unweighted peak impulse SPL (L_{peak}), using the MAX HOLD function. Use no frequency weighting, and a measurement period sufficient to include the maximum peak SPL.

Measure the A-weighted L_{eq} by setting the ISLM to A-weighting and rms detection. The measurement period must begin after the start of the scan and end prior to the scans completion. Repeat the measurements for the same protocols using other slice orientations to obtain the worse case L_{eq}.

C. Acceptance

The measured SPLs should be less than those specified.

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APPENDIX: TESTING OF VISUAL DISPLAY AND HARD COPY SYSTEMS[24]

1. Visual displays

Clean the visual display with an appropriate cleaner and soft cloth. Include the front and back surfaces of any autoreflective screens, and the front surface of the cathode ray tube (CRT). Reduce the room illumination to the normal viewing level. A room illuminance level of 5 to 10 lux is recommended.

Display the Society of Motion Picture and Television Engineers (SMPTE) digital test pattern. Adjust the window width to just encompass the range of numbers comprising the SMPTE test pattern. Adjust the window level to either the lower or middle value of the window (depending on the particular software), so that the entire test pattern is visible.

Turn the brightness and contrast controls completely counterclockwise. Increase the brightness level until the video master pattern is just visible on the display. Increase the contrast level until the image is bright and clear, and, the 95% and 100% patches are clearly separated. Do not increase the contrast to the point where the alphanumerics are blurred, smeared, or streaked on the display.

Examine the displayed image. The 5% patch should be just visible inside of the 0% patch. The area of the 0% patch should be almost black with raster lines just barely visible. The 95% patch should be visible inside the 100% patch. The alphanumerics should be sharp and clear.

TABLE II. Set-up densities and density differences of SMPTE test pattern for (CT, MRI, and DSA).

SMPTE patch	Video hard-copy camera setup[a]	Laser camera set-up[b]
0%		2.45 ± 0.10
10%	1.80 ± 0.10	2.00 ± 0.10
40%	1.15 ± 0.08[c]	1.15 ± 0.08
70%	0.50 ± 0.05	0.65 ± 0.05
90%	0.28 ± 0.03	0.35 ± 0.03[d]

[a] Kodak NMB film.
[b] Kodak SO-497 film.
[c] Tighter limits on set-up assures that service engineers set densities closer to operating level.
[d] Due to slightly high base-plus-fog of 0.24.

Note that some video monitors do not have adequate "black clamp". This means that the darker areas of the image may increase in brightness as the contrast is increased. In this case, the brightness level will have to be decreased as the contrast is increased.

2. Hard copy camera

Assure that the photographic processor is operating optimally. Clean all optical surfaces with the appropriate cleaner and lens cleaning tissue, including the front of the CRT and the folding mirror. Display the SMPTE test pattern as described in the Visual Display section.

Adjust the hard-copy camera controls so that the film densities provided in Table II are obtained for the appropriate patches of the grey scale. Examine the hard-copy image and compare it to the visual display. The two changes should appear similar.

Note that if the density of the 0% patch is increased above 2.2, the visibility of higher densities will be compromised. If more contrast in clinical images is desired the window level should be adjusted.

[a] Task Group No. 6 is part of the AAPM Nuclear Magnetic Resonance Committee, Ronald R. Price, Chairman.

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