1. OWNER DESIGN REQUIREMENTS & NEED FOR DESIGN

- The Magnetic Resonance Imaging Accreditation Program of the American College of Radiology was established to attest to the quality of the performance of magnetic resonance imaging at accredited facilities. Accreditation received through this program assures patients, referring physicians and others that magnetic resonance imaging studies at accredited sites are only performed by well-trained and competent personnel using properly functioning equipment.

All sites accredited by the American College of Radiology in magnetic resonance imaging have agreed to carry out a continuous program of magnetic resonance imaging equipment quality control. The Committee on MRI Accreditation has received many inquires regarding what would constitute an adequate magnetic resonance imaging equipment quality control program and what the appropriate roles of various health care professionals at these clinics should be.

This manual is designed to assist facilities in testing and maintaining their magnetic resonance imaging equipment in accordance with the broad principles delineated in the ACR-AAPM Technical Standard for Diagnostic Medical Physics Performance Monitoring of Magnetic Resonance Imaging Equipment [Res. 34–2014]. The committee has applied these principles to describe which personnel are responsible for which specific tasks and delineate methods for evaluating equipment performance with many tests using the American College of Radiology’s magnetic resonance imaging phantom.

Members of the ACR Subcommittee on MRI Accreditation physics who generously donated their time and experience to produce the ACR Magnetic Resonance Imaging Quality Control Manual are listed on the title page. Special thanks goes to Pamela Wilcox, executive vice president of Quality & Safety, and Leonard Lucey, senior director of accreditation, who have kept this project and the other ACR accreditation programs on track over the years.

2. ENGAGING DESIGN CONSULTANTS

A. The Supervising Radiologist

The supervising radiologist’s specific responsibilities in MRI QC are to:

1. Ensure that technologists have adequate training and continuing education in MRI.

2. Provide an orientation program for technologists based on a carefully established procedures manual (see Section E).

3. Ensure that an effective QC program exists for all MR imaging performed at the site. The supervising radiologist should provide motivation, oversight, and direction to all aspects of the QC program.

4. Select the technologist to be the primary QC technologist, performing the prescribed QC tests.

5. Ensure that appropriate test equipment and materials are available to perform the technologist’s QC tests.

6. Arrange staffing and scheduling so that adequate time is available to carry out the QC tests and to record and interpret the results.

7. Provide frequent and consistent positive and negative feedback to technologists about clinical image quality and QC procedures.

8. Participate in the selection of a qualified medical physicist or MRI scientist who will administer the QC program and perform the physicist’s tests.

9. Review the technologist’s test results at least every three months, or more frequently if consistency has not yet been achieved.

10. Review the results of the qualified medical physicist or MRI scientist annually, or more frequently when needed.

11. Oversee or designate a qualified individual to oversee the MRI safety program for employees, patients, and other individuals in the surrounding area.

12. Ensure that records concerning employee qualifications, MRI protocols, and procedures, QC, safety, and protection are properly maintained and updated in the MRI QA Procedures Manual (Section E)

B. All MRI Radiologists (Interpreting Physicians)

Responsibilities of all MRI radiologists (interpreting physicians) in MRI QC are to:

1. Ensure that established protocols are followed.

2. Follow the facility procedures for corrective action when asked to interpret images of poor quality.

3. Participate in the facility’s practice improvement program.

4. Provide documentation of their current qualifications to each MRI facility where they practice, according to the ACR

Accreditation Program and local rules.

C. Interpretive Quality Assurance

In addition, the radiologist needs to be involved in an ongoing process of QA to assess the quality of MRI interpretation. Such a program should include the following:

• A double reading in which two physicians interpret the same study

• A process that allows a random selection of studies to be reviewed on a regularly scheduled basis

• Exams and procedures representative of the actual clinical practice of each physician

• Reviewer assessment of the agreement of the original report with subsequent review (or with surgical or pathological findings)

• A classification of peer-reviewed findings with regard to level of quality concerns (e.g., a 4-point scoring scale)

• Policies and procedures for action on significant discrepant peer-reviewed findings for the purpose of achieving quality outcomes improvement

• Summary statistics and comparisons generated for each physician by modality

• Summary data for each facility/practice by modalityProcedures for interpretive QA are not specifically addressed in this manual.

The QC tests outlined in this ACR Quality Control Manual are divided into a MRI Technologist’s Section and a Medical Physicist/MRI Scientist’s Section. Relevant tests are described in detail in a “cookbook” style in these two accompanying sections. The radiologist should ensure that these sections are available to the appropriate personnel.

D. Radiologist’s Leadership Role in MRI Quality Control

1. Radiologists performing MRI must assume the primary responsibility for the quality of MRI and for the implementation of an effective QA program at their site. The staff ’s commitment to high quality will often mirror that of the radiologist in charge. The individuals performing QC tests need to know that the radiologist understands the program and is interested in the results. The radiologist needs to review the test results and trends periodically and provide direction when problems are detected.

2. The radiologist must make sure that adequate time is available for the QC program. Most tests take little time (see the MRI Technologist’s Section, Table 1). However, the necessary time must be incorporated into the daily schedule.

3. To ensure consistency in QC test performance, a single technologist should be selected for each MRI system. It is not desirable, for example, to rotate this assignment among a group of technologists. Such a practice would introduce into the test results variability extraneous to the items being tested.

4. A qualified medical physicist or MRI scientist on-site (or one who is readily available) should administer each facility’s QC program, perform the tests designated as medical physicist QC tests and oversee the work of the QC technologist(s). Where this is not feasible and during the MRI scientist’s or qualified medical physicist’s absence, the radiologist should oversee the QC program.

5. The radiologist is ultimately responsible for the quality of images produced under his or her direction and bears ultimate responsibility for both proper QC testing and QA procedures in MRI.

3. FUNCTIONAL DESIGN BRIEF & DESIGN NEEDS

A. Quality Assurance

Quality assurance in MRI is a comprehensive concept that comprises all of the management practices developed by the MR imaging team led by the MR supervising radiologist to ensure that:

1. Every imaging procedure is necessary and appropriate to the clinical problem at hand

2. The images generated contain information critical to the solution of the problem

3. The recorded information is correctly interpreted and made available in a timely fashion to the patient’s physician

4. The examination results in the lowest possible risk, cost, and inconvenience to the patient consistent with objectives above.

B. Quality Assurance Committee

The QA program includes many facets, including efficacy studies, continuing education, QC, preventive maintenance, safety, and calibration of equipment. An essential part of the QA program is the QA Committee (QAC). This group has responsibility for oversight of the program, setting the goals and direction, determining policies, and assessing the effectiveness of QA activities. The QAC should consist of the following:

• One or more radiologists

• A qualified medical physicist or MRI scientist

• A supervisory MR technologist

• Other radiology department personnel involved in caring for MRI patients, including a nurse, desk attendant, medical secretary, or others

• Personnel outside the radiology department, including medical and paramedical staff such as referring physicians Anyone who helps provide care to the patient to be studied with MRI should be considered as a possible member of the QAC because his or her efforts affect the quality of care and the satisfaction of the patient.

C. Quality Control

Quality control is an integral part of quality assurance. Quality control is a series of distinct technical procedures that ensure the production of a satisfactory product, in this case, high-quality diagnostic images. Four steps are involved:

1. Acceptance testing to detect defects in equipment that is newly installed or has undergone major repair.

2. Establishment of baseline performance of the equipment

3. Detection and diagnosis of changes in equipment performance before they become apparent in images

4. Verification that the causes of deterioration in equipment performance have been corrected Acceptance testing should take place before the first patient is scanned and after major repairs. Major repairs include replacement or repair of the following subsystem components:

• Gradient amplifiers

• Gradient coils

• Magnet

• Radiofrequency (RF) amplifier

• Digitizer boards

• Signal processing boards

A baseline check should be carried out on the MRI system as a whole and on additional subsystems, such as repaired, replaced, or upgraded RF coils. All records should be kept at a central location near the MRI scanner(s).

Specifics of the QC program for MRI are provided by the ACR in this manual.

4. DESIGN MANAGEMENT PLAN

- Introduction

Magnetic resonance imaging (MRI) is now a mature and widely used imaging method. There is significant variability, however, in the quality of MRI exams performed at different sites. Achieving the full potential of MRI requires careful attention to quality assurance (QA), both in regard to equipment performance and to the execution of imaging studies. In response to the concerns of both referring physicians and those institutions reimbursing for the costs of performing MRI, the American College of Radiology (ACR) has initiated a voluntary MRI accreditation program. This program has followed the approach of the ACR Mammography Accreditation Program, which has established practices and standards for QA and quality control (QC) in mammography. The MRI Accreditation Program looks at the general practice of clinical MRI. Specific clinical examinations and QC data are required. Sites are asked to send their best examinations for selected clinical studies for peer-review. As part of the program, QC data must be collected using a head phantom test object. During this time, the ACR has also developed specific standards related to MRI and appropriateness criteria. With improved standards, widely accepted acknowledgment of the worth of accreditation, and a growing body of criteria underpinning MRI practice, the ACR Committee on Standards and Accreditation (now called the Commission on Quality and Safety) recognized the need to reassess the mechanisms by which a radiology department or MRI clinic maintains high quality over time. Quality radiological care, long envisioned as something that flowed directly from the radiologist, has become the responsibility of the entire radiology group, including MRI technologists, qualified medical physicists, qualified MRI scientists, administrators, service engineers, nurses, and other physicians. All of these individuals play a part in maintaining quality and guaranteeing beneficial outcomes. The process, rather than the individual, is the focus of continuous QA and analysis.

The key to continuous quality improvement is a vigorous and adaptive QA program. The Radiologist’s Section details the radiologist’s responsibilities in an ongoing MRI QC program. The MR supervising radiologist has the responsibility for ensuring that all QA requirements are met. The qualified medical physicist/MRI scientist is responsible for overseeing all equipment-related QA practices. The QC technologist is specially trained and given responsibility to conduct QA/QC activities not assigned to the lead MRI radiologist or the medical physicist/MRI scientist, including weekly QC testing of the MRI system. Details of the tests to be performed by the technologist and the qualified medical physicist/MRI scientist are given in two separate sections, the MRI Technologist’s Section and the Medical Physicist/MRI Scientist’s Section. The stated frequency for QC tests is a minimum frequency. A test should be done more frequently when it is being introduced and whenever inconsistent results are found. In addition, it is important to adopt the attitude that QA and QC are continuous, not episodic, processes.

An effective QC program will not eliminate all problems but can allow for the identification of problems before they seriously affect clinical results. QC in more recently developed clinical applications such as magnetic resonance (MR) angiography, cardiac MRI, diffusion-weighted and susceptibility-weighted MRI, MR elastography, MR spectroscopy, functional MRI, and MR image-guided biopsy and therapy have not been addressed in this manual.

The radiologist and technologist must look at every study with QA in mind. Deviations from high-quality performance may occur quickly or gradually. Abrupt changes in quality may be detected during routine clinical work. More gradual or subtle changes may require regular QC testing for detection. The QC program provides a framework within which even gradual or subtle problems can be identified, isolated, and resolved.

- Overview

Table 1. Minimum Frequencies of Performing Technologist’s QC Tests

Procedure Minimum Frequency Approx. Time (min)

Setup Weekly--------------------7\*

Table Position Accuracy Weekly--------------------3

Center Frequency/Transmitter-Gain or Attenuation Weekly--------------------1

Geometric Accuracy Measurements Weekly--------------------2\*

High-Contrast Spatial Resolution Weekly--------------------1

Low-Contrast Detectability Weekly--------------------2

Artifact Evaluation Weekly--------------------1

Film Printer Quality Control (if applicable) Weekly--------------------10

Visual Checklist Weekly--------------------5

\*Some measurement can be performed simultaneously

The table provides an overview of the technologist’s QC tests; it lists the required procedures, the minimum frequency for performing each test, and approximately how long each task should take.

The MRI technologist, qualified medical physicist or MRI scientist, and radiologist constitute a QC team. It is important that they work together as a team. Each should be aware of the others’ responsibilities, especially as they relate to their own. With respect to the technologist, the qualified medical physicist or MRI scientist has two important QC functions:

• The qualified medical physicist or MRI scientist is responsible for verifying the correct implementation and execution of the technologist’s QC procedures. Normally this will entail some supervision and guidance from the qualified medical physicist or MRI scientist at the initiation of the QC program. The qualified medical physicist or MRI scientist must conduct a review of the QC log maintained by the technologist on an annual basis, although a quarterly review is preferred.

• The qualified medical physicist or MRI scientist is a resource to answer questions concerning image quality and to provide assistance in identifying and correcting image quality problems. Note: If the medical physicist determines that there is a need for corrective action, the facility should provide a copy of its medical physicist’s full report to its equipment service engineer.

With respect to the technologist, the radiologist has three important QC roles:

• The radiologist informs the technologist about image quality problems noticed in the course of interpreting clinical images. This is often the first indicator of a QC problem.

• When image quality problems arise, the radiologist decides whether patient studies can continue or must be postponed pending corrective action.

• The radiologist participates in the initial assessment of image quality at establishment of the QC program, and is responsible for monitoring QC results.

A. SETUP & TABLE POSITION ACCURACY

- Objective

To determine that the MRI scanner is performing patient setup, data entry, and prescan tasks properly.

- Frequency

Weekly

- Required Equipment

The ACR MRI phantom is used. Data are recorded on the Data Form for Weekly MRI Equipment Quality Control (Section VIII.A).

1. Place the ACR large phantom in the head coil or, for extremity MRI units, place the small phantom in the knee coil, in accordance with the instructions that came with the phantom. To ensure good reproducibility of the measurements, it is important to place the phantom in the same position, properly centered and square within the coil, each time. On the anterior side of the ACR large phantom (the side labeled “NOSE”), there is a black line running in the head-to-foot direction to help align the phantom squarely and a small positioning cross-line used to center the phantom. Because of its small size it can be difficult to use to ensure that the phantom is positioned squarely within the magnet. It is generally easier, and more reproducible, to observe the laser on the top of the grid structure inside the phantom. Position the phantom so that the axial alignment light is on the superior (head direction) edge of the grid structure. By ensuring that the thickness of the line is uniform along the edge, you will prevent any “yaw” in the phantom, assuming that the axial light is square. See Figure 1.

The small phantom should be centered and aligned as a knee would be positioned in the knee coil. Position the laser in a similar fashion to that described above for the large phantom. Move the phantom into the magnet to the proper location for scanning.

It is recommended that a three-plane localizer be used initially to ensure the phantom is properly positioned. In particular, examine the coronal image to ensure that the phantom is not rotated about the anterior/posterior axis and the sagittal image to ensure it is not tipped front-to-back. The localizer images cannot replace the sagittal sequence listed below because these fast localizer images do not have adequate spatial resolution to permit accurate prescription of axial slices, measurement of phantom length, or evaluation of table position.

2. The ACR sagittal localizer sequence should use the following parameters: For the large phantom: 1 slice, sagittal spin-echo, TR=200 ms, TE=20 ms, slice thickness=20 mm, FOV=25 cm, matrix=256 × 256, NEX=1, scan time: 51-56 seconds (s). For the small phantom: 1 slice, sagittal spin-echo, TR=200 ms, TE=20 ms, slice thickness=20 mm, FOV=12 cm, matrix=152 × 192, NEX=1, scan time: 32 s. If the 20-mm thick slice causes artifacts, a 10-mm slice may be used.

- Data Interpretation & Corrective Action

If the positioning laser is properly calibrated and the table positioning system functions properly, the superior edge of the grid structure should be at magnet isocenter. Every vendor provides a method to determine the S/I or z-coordinate of a location in the image. It usually entails placing a cursor or a region of interest (ROI) on the image and then reading the z coordinate or S/I value (Figure 2). If the location of the superior edge of the grid structure is within ±5 mm of the magnet isocenter, enter “YES” in column 2, “Table position accuracy OK?” of the Data Form for Weekly MRI Equipment Quality Control (Section VIII.A).

If the computer booted without a problem and the scanner interface (including mouse, keyboard and display) works properly, enter “YES” in column 3, “Console OK?” of the Data Form for Weekly MRI Equipment Quality Control (Section VIII.A). If there are problems with either the table or the console, note these problems (right margin of data sheet) and contact the MRI service organization following the QC procedure. Proceed with part B.

B. Axial Image Data: Prescan Parameters

1. Center Frequency

Prior to the performance of any imaging protocol, it is essential that the MRI system is set on resonance. MRI system manufacturers provide specific user protocols for resonance frequency adjustment, and most are completely automated. The phantom is positioned in the center of the magnet (with all gradient fields turned off), and the RF frequency is adjusted by controlling the RF synthesizer center frequency to achieve maximum signal. Operating an MRI scanner off-resonance reduces an image’s signal-to-noise ratio (SNR), adversely affecting LCD.

Resonance frequency checks are especially important for mobile units and resistive magnet systems that undergo frequent ramping of the magnetic field. Changes in the resonance frequency reflect changes in the static magnetic field (B0). Changes in the B0 field may be due to superconductor “run down” (typically less than 1 ppm per day on superconducting magnets), changes in current density due to thermal or mechanical effects, shim-coil changes, or effects due to external ferromagnetic materials.

- Frequency

Weekly

The ACR MRI phantom is used to acquire all image data. Data are recorded on the Data Form for Weekly MRI Equipment Quality Control (Section VIII.A).

1. Determine where the center frequency and transmitter attenuation are displayed during the prescan portion of test phantom series. The scanner, prior to image acquisition, generally determines the center frequency automatically. This information is not normally annotated on the images but is often included on a page of scan parameters that can be accessed by the user at the scanner console. Some scanners also display the center frequency on the console at the conclusion of the automated prescanning adjustments. Information on how to find the center frequency for any particular scanner usually can be obtained from the scanner user’s manual, the MRI system vendor’s applications specialist or the service engineer.

2. Display the central, sagittal slice through the ACR phantom acquired in the previous test to prescribe slice locations of the axial T1-weighted series. For the large phantom, the recommended slice prescription is 11 slices, starting at the vertex of the crossed 45° wedges at the inferior end of the ACR phantom and ending at the vertex of the crossed 45° wedges at the superior end of the phantom (Figure 3a). For the small phantom, the recommended slice prescription is seven slices, slice 1 is centered on the vertex of the angle formed by the cross wedges at the indicated end of the phantom. This prescription is cross-referenced onto the sagittal localizer (Figure 3b).

3. Set up the acquisition of the axial slices through the length of the phantom, making sure that the slice prescription is referenced to structures in the phantom in a reproducible way, and at least one of the slices lies in the uniform region of the phantom. The recommended sequence for this acquisition for the large phantom is the ACR T1-weighted axial series: 11 slices, spin-echo, TR=500 ms, TE=20 ms, FOV=25 cm, slice thickness=5 mm, slice gap=5 mm, matrix=256 × 256, NEX=1. The recommended sequence for this acquisition for the small phantom is the ACR T1-weighted axial series: 7 slices, spin-echo, TR=500 ms, TE=20 ms, FOV=12 cm, slice thickness=5 mm, slice gap=3 mm, matrix=152 × 192, NEX=1.

4. During the prescan, the system will automatically check the center frequency and set the transmitter attenuation or gain.

- Data Interpretation & Corrective Action

1. Record the center frequency and RF transmitter attenuation or gain values in the fourth and fifth columns of the Data Form for Weekly MRI Equipment Quality Control (Section VIII.A).

2. If the prescribed action limit (entered on the top line of the data form) is exceeded, repeat the prescan and record the measurement.

3. If the action limit is still exceeded, consult with the qualified medical physicist/MRI scientist regarding the excessive change in the measured frequency of the ACR imaging series. Notify the service engineer of this result.

Resonance frequency should be recorded in the Data Form for Weekly MRI Equipment Quality Control (Section VIII.A) for trend analysis. The action limits for center frequency are expressed in terms of the permissible weekly change in hertz perweek. Typically for superconducting magnets the change from week to week should be less than few parts per million (ppm). Parts per million can be converted to hertz by multiplying by the Larmor frequency (in megahertz). For example, for a 1.5T scanner, the Larmor frequency is about 64 MHz. Therefore, 1 ppm equals about 64 Hz; 2 ppm equals 128 Hz. For a 3T scanner, the Larmor frequency is about 128 MHz, so 1 ppm equals 128 Hz and 2 ppm equals 256 Hz. If the action limit for center frequency is set at 2 ppm per week, then a 1.5T scanner should change center frequency by no more than 128 Hz from one week to the next, whereas a 3T scanner’s center frequency should change by no more than 256 Hz from one week to the next.

If the recorded center frequency value exceeds the action level established by the qualified medical physicist or MRI scientist, the test should be repeated. If the center frequency change still exceeds the action level following a repeat scan, the service organization and the qualified medical physicist or MRI scientist should be contacted.

Mobile MRI systems and resistive magnets should be reset to consistent field strength after the magnet has been ramped down and powered back up. Superconducting magnets may also have their field strengths adjusted on occasion. These procedures should be recorded in the service log and noted in the Data Form for Weekly MRI Equipment Quality Control (Section VIII.A).

2. Transmitter Gain or Attenuation

After establishing the resonant frequency, the system acquires several signals while varying the transmitter attenuation (or gain) level so that imaging can proceed using the proper flip angles. Significant fluctuations in the transmitter attenuation (or gain) levels suggest problems with the RF chain.

- Frequency

Weekly

- Required Equipment

ACR MRI Phantom and Data Form for Weekly MRI Equipment Quality Control (Section VIII.A)

- Test Procedure

1. Determine where the transmitter (TX) attenuation or gain is displayed on the scanner console.

2. Record the value displayed in column 5 on the Data Form for Weekly MRI Equipment Quality Control (Section VIII.A).

3. If the change in decibels (dB) exceeds the action limits, report the problem to the qualified medical physicist or MRI scientist.

- Data Interpretation & Corrective Action

Transmitter (TX) attenuation or gain values are usually recorded in units of dB. This engineering system takes advantage of a logarithmic scale so that values over a large dynamic range can be easily related. However, a small change in dB represents a large change in the transmitter attenuation if displayed using a linear scale (volts or watts). Changes in the measured TX attenuation or gain exceeding the action limits should be reported to the qualified medical physicist/MRI scientist and the site service engineer.

C. Image Data Measurements

- Objective

Weekly image quality measurements ensure accurate calibration of the MRI system. Three specific measurements are to be performed weekly: geometric accuracy, limiting spatial resolution, and LCD. Each of these measurements is addressed specifically below.

1. Geometric Accuracy Measurements

In MRI, the radiologist assumes that the geometric relationships are accurate and concentrates on deciphering the tissue contrast relationships for a variety of pulse sequences to make an accurate diagnosis. However, the geometric relationships in the MR image can easily be in error by a factor of 5%–10% if care is not taken to ensure the gradient-scaling factors are properly calibrated and the magnet field is very homogeneous.

The objective of the following tests is to verify that the image is scaled in a manner reflecting the true dimensions of the body part under investigation.

- Frequency

Weekly

- Required Equipment

Geometric accuracy is checked with the ACR MRI accreditation phantoms using the sagittal localizer image and image slice 5 from the T1-weighted ACR axial series for the large phantom (or sagittal localizer image and slice 3 for the small phantom). These data are analyzed in the following manner. Data are recorded on the Data Form for Weekly MRI Equipment Quality Control (Section VIII.A).

- Test Procedure

The display window and level should be set so that the edges of the phantom are approximately at the half-maximum value of the signal intensity. To set the appropriate display values, follow this procedure:

1. Setting the Window and Level

a. Set the window width to a very narrow value (zero or one). Adjust the window level until about one-half of the fluid within the phantom is white and the other half is black. Note the window level value.

b. Change the window width value to the window level value noted in step 1a.

c. Change the window level value to one-half of the window width value that was set in step 1b.

2. Sagittal Image Measurement

a. Display the sagittal image of the phantom using the procedure described above to set the display window width and level.

b. Using the distance-measuring function, measure the length from one end of the signal-producing region of the phantom to the other (Figure 4).

c. Verify that the length is measured along a line that runs vertically from one end of the phantom to the other and is close to the center of the phantom.

d. Enter the resulting length (in millimeters) in column 6 (z-direction) of the Data Form for Weekly MRI Equipment Quality Control (Section VIII.A)

3. Transaxial Image Measurements

a. Display slice 5 for the large phantom and slice 3 for the small phantom in normal mode (Figure 5).

b. Since these distance measurements are dependent on the window setting, use the standard routine for setting window width and level routine described above in step 1.

c. Use the scanner’s distance-measuring function to determine the diameter of the signal-producing circular phantom, measured vertically through the center of the phantom.

d. Enter the resulting length (in millimeters) in column 7 (y-direction) of the Data Form for Weekly MRI Equipment Quality Control (Section VIII.A).

e. Use the scanner’s distance-measuring function to determine the diameter of the signal-producing circular phantom, measured horizontally across the center of the phantom.

f. Enter the resulting length (in millimeters) in column 8 (x-direction) of the Data Form for Weekly MRI Equipment Quality Control (Section VIII.A)

- Data Interpretation & Corrective Action

1. Geometric accuracy measurements on the ACR MRI accreditation phantom, when measured over a 25-cm field-of-view for the large phantom and a 10-cm field of view for the small phantom are generally considered acceptable if they are within ±2 mm of the true values. Depending on the mix of studies at a given site, the qualified medical physicist or MRI scientist may determine that a more strict action limit should be put in place.

2. If the length or either diameter measurement of the phantom exceeds the action level established by the qualified medical physicist or MRI scientist, the QC technologist should carefully inspect the magnet bore or gap to verify that no ferromagnetic material (hair pins, paper clips, etc.) has found its way near the imaging volume.

3. The measurement should then be repeated.

4. If the length or either diameter measurement of the phantom exceeds the action level following a repeat measurement, the service engineer and the qualified medical physicist or MRI scientist should be contacted. The service engineer should be able to correct improper gradient field calibrations through a vendor recommended procedure.

The most common cause of failure of this test is one or more miscalibrated gradients. A miscalibrated gradient causes its associated dimension (x, y, or z) in the images to appear longer or shorter than it really is. It will also cause slice-position errors. It is normal for gradient calibration to drift over time and to require recalibration by the service engineer.

Gradient amplifiers need time to warm up and stabilize when they are turned on. Some sites power off their scanner hardware, including gradient amplifiers, overnight. Those sites should make sure their hardware has been on at least an hour before acquiring images of the phantom.

Another possible cause of failure is use of a very low MRI receiver bandwidth. It is common practice on some scanners and at some facilities to reduce receiver bandwidth to increase SNR. This strategy can be pushed to the point that magnetic field inhomogeneities manifest themselves as large spatial distortions in the image. On most scanners the default bandwidth for T1-weighted acquisitions is set high enough to avoid this problem. If the geometric accuracy test exceeds the action limits and the ACR T1-weighted series (described above) was acquired at low bandwidth, one should try to acquire these images again at a larger bandwidth to see if the problem is eliminated.

B0 field inhomogeneities could be caused by improper adjustment of the gradient offsets, improper adjustment of passive or active magnet shims, or a ferromagnetic object such as a pocket knife or large hair clip lodged in the magnet bore. Especially on open magnet systems, which have relatively small volumes of gradient linearity and B0 homogeneity, it is possible that abnormally high B0 field inhomogeneities could cause significant dimensional errors in the phantom images. The service engineer can easily measure the magnet homogeneity, and any inhomogeneity large enough to cause failure of the geometric accuracy test should be correctable.

2. High-Contrast Spatial Resolution

The high-contrast spatial resolution test assesses the scanner’s ability to resolve small objects. This is sometimes called “limiting spatial resolution.”A failure of this test means that for a given field of view and acquisition matrix size the scanner is not resolving small details as well as normal for a properly functioning scanner.

- Frequency

Weekly

- Required Equipment

High-contrast resolution is checked with the ACR MRI accreditation phantom using image slice 1 from the T1-weighted ACR axial series. These data can be analyzed in the following manner.

- Test Procedure

For this test, one visually determines the number of individual small bright spots in arrays of closely spaced fluid-filled holes drilled in a small block of plastic (called the resolution insert). The resolution insert is located in slice 1 of the ACR T1-weighted axial image series (Figure 6).

Note that there are three pairs of not-quite-square arrays of holes in the insert. The insert consists of an upper-left (UL) hole array and a lower-right (LR) hole array, where right and left are the viewer’s right and left. The UL and LR arrays share one hole in common at the corner where they meet. The UL array is used to assess resolution in the right-left direction, and the LR array is used to assess resolution in the top-bottom direction (i.e., anterior-posterior if this phantom were a head).

The UL array comprises four rows of four holes each. The center-to-center hole separation within a row is twice the hole diameter. The center-to-center row separation is also twice the hole diameter. Each row is staggered slightly to the right of the one above, which is why the array is not quite square.

The LR array comprises four columns of four holes each. The center-to-center hole separation within each column and the center-to-center spacing between columns are twice the hole diameter. Each column is staggered slightly downward from the one to its left.

The hole diameter for the large phantom differs between the array pairs: for the left pair it is 1.1 mm; for the center pair it is 1.0 mm; and for the right pair it is 0.9 mm. The hole diameter of the small phantom differs between the array pairs: for the left pair it is 0.9 mm; for the center pair it is 0.8 mm; and for the right pair it is 0.7 mm. Thus, using this insert, one can determine whether or not resolution has been achieved at each of these three hole sizes.

For this test, high-contrast spatial resolution in slice 1 of the ACR T1-weighted axial series is evaluated. The following procedure is repeated for each of those series:

1. Display the image of slice 1.

2. Magnify the image by a factor between two and four, keeping the resolution insert visible in the display.

3. Set the window width to a small value (<10% of the entire range of signal intensities for the image). Adjust the window level until the holes in the resolution insert are individually displayed.

4. Begin with the leftmost pair of hole arrays, which is the pair with the largest hole size (large phantom: 1.1 mm; small phantom: 0.9 mm).

5. Look at the rows of holes in the UL array and adjust the display window and level to best show the holes as distinct from one another.

6. If all four holes in any single row are distinguishable from one another, the image is considered resolved right-to-left (horizontally) at this particular hole size.

7. Enter the smallest hole size (1.1, 1.0, or 0.9 mm for the large phantom and 0.9, 0.8, or 0.7 mm for the small phantom) that can be resolved horizontally in the UL array in column 9 of the Data Form for Weekly MRI Equipment Quality Control (Section VIII.A). That is the measured horizontal spatial resolution.

8. Look at the columns of holes in the LR array and adjust the display window and level to best show the holes as distinct from one another.

9. If all four holes in any single column are distinguishable from one another, the image is considered resolved top-to-bottom (vertically) at this particular hole size.

10. Enter the smallest hole size (1.1, 1.0, or 0.9 mm for the large phantom and 0.9, 0.8, or 0.7 mm for the small phantom) that can be resolved vertically in the LR array in column 10 of the Data Form for Weekly MRI Equipment Quality Control (Section VIII.A). That is the measured vertical spatial resolution.

- Data Interpretation & Corrective Action

One needs to be very clear about what is meant by the word “distinguishable.” It is not required that image intensity drop to zero between the holes; that is not normal. However, one must find a single window and level setting such that all four holes in at least one row are recognizable as points of brighter signal intensity than the spaces between them.

When the hole size is comparable to the resolution in the image, there is a tendency for groups of two or more holes in a row to blur together and appear as a single irregularly shaped spot of signal. In this case the holes in that row are considered unresolved.

Sometimes one or more holes, which are distinguishable from their neighbors in their own row, blur together with their neighbors in adjacent rows. This is acceptable and does not affect the scoring for the row.

For the large phantom, the field of view and matrix size for the ACR T1-weighted axial series are chosen to yield a nominal resolution of 1.0 mm in both directions. For both directions in the axial T1-weighted ACR series, the measured resolution should be 1.0 mm or better. On many scanners, one can distinguish the holes in the 0.9 mm arrays in one or both directions. The resolution of the MRI system should not change. For the small phantom, the field of view and matrix size for the axial ACR series are chosen to yield a resolution of 0.8 mm in both directions.

Changes in high-contrast spatial resolution can be due to the gradient field strength, the eddy current compensation, and/or the main (B0) magnetic field homogeneity being out of calibration. These problems will often produce poor results in other QC tests described in this manual. Unstable gradient amplifiers also have been known to cause subtle decreases in spatial resolution. Consult with the qualified medical physicist/MRI scientist regarding any change in the measured resolution of the axial ACR imaging series.

3. Low-Contrast Detectability

- Objective

The low-contrast detectability (LCD) test assesses the extent to which objects of low contrast are discernible in the images. For this purpose the ACR MRI accreditation phantom contains contrast objects of varying size and contrast. The detection of a low-contrast object is primarily determined by the contrast-to-noise ratio achieved in the image, and may be degraded by the presence of artifacts such as ghosting.

The ACR MRI accreditation phantom contains low-contrast objects of varying size and contrast that appear on four slices of the T1-weighted axial multislice series (Figure 7): 8 through 11 for the large phantom and 6 and 7 for the small phantom. In each slice the low-contrast objects appear as rows of small disks, with the rows radiating from the center of circle-like spokes in a wheel. Each spoke is made up of three disks, and there are 10 spokes in each circle.

All of the spokes on a given slice have the same level of contrast. For the large phantom and a 5-mm slice thickness, in order from slice 8 to slice 11, the contrast values are 1.4%, 2.5%, 3.6%, and 5.1%. For the small phantom and a 5-mm slice thickness, slices 6 and 7 have contrast values of 3.6% and 5.1%, respectively. All disks in a given spoke have the same diameter. Starting at the 12 o’clock position and moving clockwise, the disk diameters decrease progressively from 7.0 mm at the first spoke to 1.5 mm at the 10th spoke.

The low-contrast disks are actually holes drilled in thin sheets of plastic mounted in the phantom at the locations of the four slices. The contrast is derived from the displacement of solution from the slices by the plastic sheets.

The measurement for this test consists of counting the number of complete spokes seen in a designated axial slice. The specific slice designated for this weekly QC test should be determined by the qualified medical physicist or MRI scientist to be the most sensitive to deviations in system performance. Scanners differ widely in their contrast-to-noise ratio performance.

For instance in the large phantom, if a scanner depicts all of the disks in all of the spokes in slices 9, 10, and 11 using the ACR T1-weighted axial series, but only some of the spokes in slice 8, then slice 8 should be used for this test. For the small phantom, if a scanner depicts all of the spokes in slice 7 using the ACR T1-weighted axial series, then slice 6 should be used for this test. Conversely for the large phantom, if a scanner typically depicts none of the spokes in slices 8, 9, and 10, then slice 11 should be used for this test. For the small phantom, if the MRI system typically depicts none of the spokes in slice 6, then slice 7 should be used for this test. The slice number will be entered in the first row, column 11 of the Data Form for Weekly MRI Equipment Quality Control (Section VIII.A).

- Frequency

Weekly

- Required Equipment

LCD is checked with the ACR MRI accreditation phantom using image slices 8–11 for the large phantom and image slices 6–7 for the small phantom from the T1-weighted ACR axial series. These data should be analyzed in the following manner.

- Test Procedure

Use the following procedure to score the number of complete spokes seen in a slice:

1. Display the slice to be scored as prescribed by the qualified medical physicist or MRI scientist and listed in the top cell of column 11 on the Data Form for Weekly MRI Equipment Quality Control (Section VIII.A).

2. Adjust the display window width and level settings for best visibility of the low-contrast objects (Figure 7). This will require a fairly narrow window width and careful adjustment of the level to best distinguish the objects from the background. As you move from slice to slice, the window and level may require

readjustment for best visualization of low-contrast objects. Once obtained for a given scanner and slice number, the window and level should remain the same from week to week.

3. Count the number of complete spokes seen. Begin counting with the spoke having the largest diameter holes; this spoke is at 12 o’clock or slightly to the right of 12 o’clock (large phantom) or slightly left of 12 o’clock (small phantom), and is referred to as spoke 1 (see Figure 7). For the large phantom, count clockwise from spoke 1 until a spoke is reached where one or more of the holes are not discernible from the background. For the small phantom, count counterclockwise from the largest spoke.

4. The number of complete spokes counted is the score for this slice. Record the score in column 11 of the Data Form for Weekly MRI Equipment Quality Control (Section VIII.A).

5. If the action criteria are exceeded (i.e., not enough rows of low-contrast objects are detected), recheck the phantom positioning. Tilting of the phantom in the head-foot direction can be particularly troublesome (Figure 8). Verify that slices 8–11 for the large phantom (or slices 6–7 for the small phantom) are actually positioned over the thin plastic sheets in the phantom that contain the holes (Figure 9). Acquire the axial series again.

6. If the LCD test still exceeds the action criteria, contact the qualified medical physicist or MRI scientist and the service engineer.

- Data Interpretation & Corrective Action

LCD is related to the SNR of the MR image (Figure 10). However, other factors can cause a degradation of the visibility of the spokes in the LCD insert. Too low an acquisition matrix or excessive use of sharpening filters can cause excessive truncation artifacts and result in poor depiction of the outer holes in the spokes (Figure 11a). Excessive image-ghosting can result in obscuration of some of the spokes (Figure 11b). The system’s performance on this test is also sensitive to improper phantom and/or slice positioning, so positioning should be the first parameter checked if there is a large decrease in the number of spokes perceived from week to week (Figures 8 and 9).

Thus, the issue of correspondence between the number of LCD spokes and the SNR depends on proper positioning of the ACR phantom, proper placement of acquired slices, and other factors such as image artifacts. A spoke is complete only if all three of its holes are discernible. Count complete spokes, not individual holes. Sometimes there will be one or more complete spokes of smaller object size seen following a spoke that is not complete, as in Figure 8. Do not count these additional spokes. Stop counting prior to the first incomplete spoke.

Holes on the threshold of perception can be difficult to score. They may appear ragged or misshapen; that is OK. The question is not whether each test object is seen as perfectly round, but whether the object is sufficiently distinct from the background that one can say with a reasonable degree of confidence that the object is present. In making this decision it can be helpful to look at areas where there are no low-contrast objects to gauge the fluctuations in intensity from noise and artifacts that might mimic a barely discernible test object. A test object that looks similar to (or less distinct than) background noise fluctuations would not be deemed discernible.

In most cases it is not necessary to spend time pondering difficult decisions on barely visible objects; just score the test conservatively and revisit the scoring in the unlikely event the final score is below the action limit (i.e., several spokes below baseline). Typically, if the number of detected spokes is reduced by more than three, then the qualified medical physicist/MRI scientist and the service engineer should be notified. However, the qualified medical physicist or MRI scientist should determine the appropriate action limit for the MRI system and instruct the QC technologist in the appropriate manner to evaluate the visibility of low-contrast objects.

D. Artifact Evaluation

Various artifacts can occur during the weekly QC procedure that may be early indicators of declining MRI system performance. The following is a quick procedure for artifact analysis.

- Frequency

Weekly

- Required Equipment

Image artifacts are checked with the ACR MRI accreditation phantom using the image slices from the T1-weighted ACR axial series. These data can be analyzed in the following manner.

- Test Procedure

1. On each slice, adjust the display window and level to show the full range of pixel values in the image. This is difficult to do by eye because the phantom image has mostly bright and dark regions and very few intermediate gray regions to serve as a visual reference for the adjustment.

2. The easiest way to get it right is to find the approximate pixel value for the bright areas, which can be done with a region-of-interest (ROI) measurement of the mean value in a bright area. Then, set the window to that value and the level to half of that value. The values don’t have to be exact, approximate ones will do for this purpose.

3. Check that the following are true: a. The phantom appears circular, not elliptical or otherwise distorted. b. There are no ghost images of the phantom in the background or overlying the phantom image. c. There are no streaks or artifactual bright or dark spots in the image.

d. There are no unusual or new features in the image.

4. If any of the foregoing items are false, then enter “Yes” in column 12 of the Data Form for Weekly MRI Equipment Quality Control (Section VIII.A); otherwise enter “No.” If there is an artifact, then enter a description as a note. Note that ghosting is a very nonspecific symptom of a hardware problem. In general, it is caused by instability of the measured signal from pulse cycle to pulse cycle, which can have its origin in the receiver, transmitter, or gradient subsystems. Motion of the phantom can also cause ghosting. Make sure the phantom is stable in the RF coil and not free to move or vibrate. Having ruled out phantom motion, it will usually be necessary to ask the service engineer to track down and correct the cause of the ghosting. More information on ghosting is found in the Medical Physicist/MRI Scientist’s Section IV.D. Radiofrequency Coil Checks.

FILM PRINTER CONTROL

- Objective

To ensure artifact-free films are produced with consistent gray levels that match the image appearance on the filming console.

- Frequency

Operating levels should be established at the initiation of the QC program, and whenever a significant change is made in the film system, e.g., change of film type, chemicals, or processing conditions. Film printer QC is performed weekly if film is used for primary interpretation. If hardcopy images are not used for primary interpretation, this test does not need to be performed. However, if the printer is used infrequently (e.g., backup printers or ones used for occasional printing for patients), this test should be performed prior to clinical use.

- Required Equipment

1. Densitometer2. Film printer QC chart

About the SMPTE Test PatternThe SMPTE test pattern (Figure 12) created by the Society of Motion Picture and Television Engineers, is widely used for evaluating display systems for medical diagnostic imaging [3,4]. It should be available on all MRI scanners. The SMPTE pattern has several components designed to test the quality of the display. For the purposes of this procedure we are concerned only with two of those components, which are indicated in Figure 12. The first component is a ring of square patches of different gray levels ranging from 0 to 100% in increments of 10%. The second component is a pair of square gray-level patches, each with a smaller patch of slightly different gray level inside: one is a 0 patch with a 5% patch inside, and the other is a 100% patch with a 95% patch inside. These are referred to as the 0/5% patch and the 95/100% patch.

Evaluation of the SMPTE pattern as printed in hard copy provides a mechanism to verify that contrast levels observed on the system monitor match those displayed on film. For this reason the SMPTE pattern must be printed from the MRI, not from SMPTE patterns that may exist on the camera or on a PACS system.

- Operating Levels

The qualified medical physicist or MRI scientist is responsible for establishing the correct operating levels for the film printer. This procedure will be carried out when the QC program is initiated and whenever a significant change is made in the film system. The QC technologist then compares films against the established operating levels. This is done weekly to ensure consistent film quality.

- Weekly Printer Quality Control

1. Display the SMPTE test pattern on the filming console. Set the display window and level to the manufacturer-specified values for the SMPTE pattern. Do not set the window and level by eye; doing so invalidates this procedure.

2. Examine the SMPTE pattern to confirm that the gray-level display on the filming console is subjectively correct. The visual impression should be that there is an even progression of gray levels around the ring of gray-level patches. Verify that the 5% patch can be distinguished in the 0/5% patch, the 95% patch can be distinguished in the 95/100% patch, and that all the gray level steps around the ring of gray levels are distinct from adjacent steps.

If these conditions are not met, do not adjust the display window and level in an effort to correct the problem. Corrective action is needed. However, the rest of this procedure can be completed prior to taking corrective action

3. Film the SMPTE pattern. Use a 6-on-1 format and capture the pattern in all six frames to test the uniformity of response across the full film area.

4. Using a film densitometer, measure the optical density of the 0, 10%, 40%, and 90% gray-level patches of the SMPTE pattern in the upper left frame of the film.

5. Plot these optical densities in the appropriate places on the Film Printer QC chart. Circle any points that fall outside the control limits. Optical density baseline values should already have been established and entered on the chart when the operating levels were set.

6. Put the film on a light box and inspect it for streaks, uneven densities and other artifacts.

- Precautions & Caveats

The ambient lighting at the filming console should be kept very low. The monitor should be positioned so that there is no glare from room lighting. The lighting level should be kept the same whenever filming is done.

If multiple modalities (such as CT or MRI) are connected to one film printer, similar initial setup and QC testing should be performed for each printer input.

One common cause of variation beyond density control limits is changes in film emulsion batches. To reduce the need to recalibrate the film printer, do not mix emulsion batches. Instead, use up all of one emulsion number before starting to use another batch.

- Suggested Performance Criteria

Table 2 provides possible optical densities and control limits for selected SMPTE gray-level patches. These are offered as a starting point for setting up the film printer and can be adjusted according to the preferences of the supervising radiologist or on the advice of the qualified medical physicist or MRI scientist who might base the optical densities on Part 14 of the DICOM standard or on other published guidelines. If adopted, the control limits in Table 2 should not be adjusted to larger values but, in consultation with the qualified medical physicist or MRI scientist may be adjusted to smaller values. Dry-film printers, for example, might use control limits of 0.10 instead of ±0.15.

Table 2. Optical Densities and Control Limits

SMPTE Patch Optical Density Control Limits0 2.45 ±0.1510% 2.10 ±0.1540% 1.15 ±0.1590% 0.30 ±0.08

It should be noted that many modern printers perform a self-calibration each time a new package of film is loaded. These printers typically print a calibrated step pattern that is used to calibrate the system. Even for such self-calibrating printers, it is recommended that the optical densities for a SMPTE or step density pattern be measured and recorded weekly to verify consistent hardcopy performance.

- Monitor Gray-Level Failure In step 2, image display at the monitor is assessed by visual inspection of the SMPTE pattern. A failure to meet the conditions described in step 2 means the monitor is providing an incorrect gray-scale representation of the image data. This will lead the technologist to choose incorrect window and level settings when filming patient studies.

Most often the problem is caused by misadjustment of the monitor brightness and contrast. Excessive ambient lighting can also cause the problem and occasionally components of the display may need repair or replacement.

Make sure the ambient light is low and comparable to the conditions under which the data described in step 2 were acquired.

Perform the manufacturer’s recommended procedure for contrast and brightness adjustment of the monitor. If there is any doubt about the correct procedure, or if the brightness and contrast controls are not accessible, have the qualified medical physicist or MRI scientist or service engineer make the adjustments. The qualified medical physicist or MRI scientist can perform a more complete set of tests of the monitor (Medical Physicist/MRI Scientist’s Section IV.E). If there is still a problem, it will be necessary to have the service engineer correct it.

- Corrective Action

#If any optical densities fall outside the control limits, or artifacts are found, corrective action should be taken.

The following is a general procedure to use for corrective action. It is intended to provide guidance when the technologist is uncertain about how to proceed. Often the technologist will have information about the circumstances in which the problem arose and experience with the equipment that enables him or her to skip some of these steps and move more directly to the cause of a problem:

1. Repeat the QC procedure to make sure the failure is real, not an error in the measurements.

2. Check for easily corrected problems:

a. Has the film been exposed to a light leak? This causes “fogging” of the film and shows up in the measurements as elevated optical densities, with the 90% patch being most sensitive. If this problem is suspected, check the dark room for light leaks, then load a few sheets of film from a new box having the same emulsion run number, and repeat the measurements.

b. Is the correct type of film in the cassette, and is it loaded in the correct orientation?

c. Has there been a change in the type of film being used? If so, new action limits will have to be established. The qualified medical physicist/MRI scientist responsible for film QC should be informed and asked to assist with troubleshooting the problem. If the problem cannot be resolved quickly, consult with the supervising radiologist to decide whether or not filming can continue while waiting for the problem to be corrected.

VISUAL CHECKLIST

- Objective

To verify the MRI system patient bed transport, alignment and system indicator lights, RF room integrity, emergency cart, safety lights, signage, and monitors are present and working properly and are mechanically and electrically stable.

- Frequency

This test should be performed at least weekly.

- Required Equipment

Visual checklist (Section VIII.B)

- Precautions & Caveats

Some of the items on the checklist may not be present on all systems, and some may be operator convenience features. However, many of the items are essential for patient safety and high-quality diagnostic images. It may be necessary to add additional items to the list that are specific to particular equipment or procedures. These should be included on the checklist and in each evaluation.

- Suggest Performance Criteria & Corrective Action

Each of the items listed in the visual checklist should pass or receive a checkmark. Items not passing the visual checklist should be replaced or corrected immediately.

Items missing from the room should be replaced immediately. Malfunctioning equipment should be reported to the MRI service engineer for repair or replacement as soon as possible.

ESTABLISHING THE QUALITY CONTROL PROGRAM

A. Phantom Section

Currently, the ACR MRI Accreditation Program has two phantoms: large and small. The large phantom is used for whole body magnets, and the small phantom is used for extremity magnets. This manual describes the use of both phantoms.

The ACR MRI accreditation large phantom is a short, hollow cylinder of acrylic plastic closed at both ends. The inside length is 148 mm, and the inside diameter is 190 mm. The phantom is filled with a solution of nickel chloride and sodium chloride (10 mM NiCl2 and 75 mM NaCl, or 0.45% NaCl by weight). The outside of the phantom has the words “NOSE” and “CHIN” etched into it as an aid when orienting the phantom for the scanner as if it were a head.

The ACR MRI accreditation small phantom is a short, hollow cylinder of acrylic plastic closed at both ends. The inside length is 100 mm, and the inside diameter is 100 mm. It is filled with the same solution of nickel chloride and sodium chloride as the large phantom: 10 mM NiCl2 and 75 mM NaCl, or 0.45% aqueous NaCl by weight.

Both large and small ACR MRI phantoms contain a separate vial filled with 20 mM NiCl2, but with no NaCl.

Inside the phantom are structures designed for performing the following seven quantitative tests using measurements on the digital images:

1. Geometric accuracy

2. High-contrast spatial resolution

3. Slice-thickness accuracy

4. Slice-position accuracy

5. Image intensity uniformity

6. Percent signal ghosting

7. Low-contrast detectability

The ACR MRI accreditation phantoms are the recommended phantoms for weekly QC. However, if the ACR phantom is incompatible with the required test, another phantom can be used. First, the qualified medical physicist/MRI scientist should confirm that the proposed alternative phantom meets the following criteria: • It electrically loads the head coil approximately as much as a typical patient. • The T1 and T2 of the filler material are within the range of normal soft tissues (see NEMA MS 1-2008 [2]). • It is about the same size as a typical adult head, and it fits in the head coil. • It can be easily and reliably positioned in the same location and orientation every time it is used. • There is at least one location within the phantom that is free of structures and presents an area of uniform signal suitable for assessing percent image uniformity as described later. In most clinical scans, the patient is the primary source of noise [13]. To best approximate the clinical situation, the coil should be electrically loaded by using an appropriate filler material or by some other means, so that the electrical properties of the body are simulated. The NEMA standard for determining SNR in MRI (MS 1-2008) lists the coil loading characteristics appropriate for such a phantom. Note that this criterion contradicts the phantom specified in AAPM report No. 28 [14], in which a phantom filled with nonconducting material is recommended

B. Methods and Action Limits for Weekly Quality Control Tests

Effective equipment QC requires the regular assessment of system performance. Thus, measurements should be taken at least weekly to ensure that the scanner is operating effectively. The scope of these tests is constrained by a desire to complete them expeditiously. The weekly tests, which include measurement of center frequency and SNR, assessment of image quality and a check for image artifacts, can all be performed using the ACR MRI accreditation phantom. These tests are described in detail in the MRI Technologist’s Section of this manual.

MRI equipment manufacturers may have established daily methods for measuring some or all of these parameters that will likely use pulse sequences and phantoms different from those recommended by the ACR. Not all manufacturer-supplied procedures, however, are suitable. Due to economic constraints, the action levels set by vendors may be more conservative or liberal than the level of scanner quality control desired by the site. In addition, many vendors use phantoms that are filled with paramagnetic solutions having T1 values that are sensitive to changes in temperature and static magnetic field (B0) strength [15]. Some manufacturers encourage the collection of data; however, these data are not analyzed until after there is a clinical system failure, and are thus not being used as a quality control tool.

It is the task of the qualified medical physicist/MRI scientist to evaluate the methods and effectiveness of the MRI equipment manufacturer’s QC tests. The decision to use a procedure that is an alternative to the recommended tests, using the ACR MRI accreditation phantom, should only be implemented after the facility obtains a recommendation and justification from a qualified medical physicist or MRI scientist.

At a minimum, the procedure should satisfy the following criteria:

• Use the ACR phantom or an alternative phantom meeting the criteria described above.

• Acquire and reconstruct images of the phantom. It is not sufficient to acquire only raw data.

• The pulse sequence and reconstruction software should be the same as those used for clinical imaging, with sequence parameters typical of those used in clinical imaging.

• Produce and report to the user a numerical value for all test measurements. Simply reporting “pass” or “fail” is not acceptable.

• SNR values are derived from images reconstructed in the normal manner, not raw signals.

• Images produced are derived as if they were normal clinical images and may be displayed and archived as desired.

• Report the center frequency for the image acquisition or ensure that it is conveniently available to the user.

Thus, although it is important for a site to follow the vendor’s recommendations, it is not always clear that the vendor’s methods are adequate to ensure a high level of QC. The MRI Technologist’s Section describes the recommended tests, using the ACR MRI accreditation phantom. The qualified medical physicist/MRI scientist may determine when it is necessary to deviate from these tests. If this decision is made, the new procedures and their recommended action levels must be documented in detail and made available in writing, as a part of the facility’s MRI Quality Assurance Procedures Manual (Radiologist’s Section IV.E).

C. Establishing Action Limits for Weekly MR Image Quality Control Tests

It is the responsibility of the qualified medical physicist/MRI scientist to set the action limits and to ensure that they are adequately sensitive to detect MRI equipment problems. The suggested performance criteria given in this document are liberal enough that all properly functioning equipment should be able to meet them. Therefore, it is not appropriate to relax the recommended performance criteria. For MRI systems with advanced technology, the qualified medical physicist/MRI scientist may wish to tighten criteria. Failure to meet these criteria is an indication that the equipment is functioning poorly and that corrective action is required.

The normal values of LCD and center frequency are different for each scanner. LCD is strongly dependent on the sequence parameters and choice of phantom. Therefore it is necessary to begin a weekly QC program by establishing action limits (control limits) for LCD and center frequency that are appropriate to the scanner, phantom, and pulse sequence parameters used in the QC program.

First, verify that the scanner is at peak performance levels.

If the scanner has just passed its acceptance test and a set of baseline data has been established, that is sufficient verification. Otherwise, do the following:

1. Have the service engineer run the manufacturer’s diagnostic tests to confirm that the scanner is performing well as measured by those tests and that it meets all of the manufacturer’s performance specifications.

2. Review the results of the manufacturer’s diagnostic tests to provide independent confirmation that appropriate and adequate tests were run and that the test results meet manufacturer’s specifications.

3. Have the supervising radiologist examine several clinical images and confirm that the image quality is as good as expected for this make and model of scanner. For this purpose, it is better to assess the image quality from the console or a diagnostic workstation rather than from film, since that eliminates any problems with film production from the assessment.

Collect QC data for 10 days following the procedures found in the MRI Technologist’s Section of this manual. Use the MRI Equipment Performance Evaluation Data Form (MRI Technologist’s Section, Appendix VIII.A) provided in this manual to record the results. This data form with the baseline measurements should be kept in the weekly QC notebook (MRI Technologist’s Section III.C). Write the word “baseline” on the data form prominently to distinguish it from ordinary QC data.

1. Center Frequency

The resonance frequency is defined as that RF frequency (f0) that matches the B0 (in Tesla) according to the Larmor equation:

f0 = ( γ/2π) B0Where γ is the gyromagnetic ratio for the nucleus under study. For hydrogen nuclei, the quantity (γ/2π ) is 42.58 MHz/T. For a 1.5T system, the resonance frequency should be approximately 63.87 MHz.

The action limits for center frequency are expressed in terms of the permissible weekly change. Typically for superconducting magnets the change from week to week should be less than a few parts per million (ppm). Permanent magnet systems will generally exhibit greater week-to-week variation. Permissible action limits will depend upon the specific system and should be set individually by the medical physicist. Enter the action limits in the space provided on the Data Form for Weekly MRI Equipment Quality Control (MRI Technologist’s Section, VIII.A) with the baseline data.

A more complete discussion of factors affecting magnetic field drift can be found in AAPM Report No. 100 [8].

Service-related center frequency change: In the case of a service-related change in center frequency, accept the large, abrupt change in center frequency and continue applying the center frequency action criterion as before. Make an entry explaining what was done in the “QC Incidents and Actions” section of the QC notebook (MRI Technologist’s Section, III.C).

2. Transmitter Gain or Attenuation

Transmitter (TX) gain or attenuation is typically a measure of the power needed to nutate the bulk magnetization by 90°. Thus, for the same coil and phantom, TX gain should remain relatively constant if the MRI unit is performing normally. A change in this parameter may indicate a problem in some part of the RF transmitter and/or its associated coils.

Changes in TX gain are directly related to changes in SNR. This is a coarse measure for two reasons. First, the TX gain or attenuation is generally reported in decibels, a logarithmic unit. Second, these measurements usually are made over the entire volume of the central slice. Nevertheless, the RF transmitter gain measurement is a useful first check of the system and requires no extra scan time since it is measured with each prescan.

Any reduction in TX attenuation (or increase in transmitter gain) required to perform the same study on a phantom should be taken as an indication of potential MRI system problems. These problems may include impairment of the RF transmission field, degradation of the B0 magnetic field homogeneity or noise added by the RF receiver chain. Potential problems with the receiver chain electronics include noise generated by active electronic components, such as PIN diodes, or inadequate isolation between the TX and receiver (RX) channels of the system. For more detailed information, including a detailed derivation of the relationship between SNR and transmitter attenuation, the reader is referred to Redpath and Wiggins [16].

3. Geometric Accuracy Measurements

Geometric accuracy is a term used to describe the degree of geometrical distortion present in images produced by the MRI system. Geometric distortion can refer to either displacement of displayed points within an image relative to their known location or improper scaling of the distance between points anywhere within the image. In terms of the weekly image QC tests, the technologist is concerned only with the issue of proper scaling. This is because measurements are made only along the central axes of the ACR MRI phantom. However, the qualified medical physicist/MRI scientist should also examine image displacement and distortion as part of the annual review and should calculate and record the percent geometric distortion (%GD).

%GD= (true dimension-observed dimension/true dimension) × 100

Geometric distortion may be measured between any two points within the field-of-view (FOV) provided that pixel resolution is not a significant source of error. Most modern MRI systems can achieve a %GD of less than ±1%, which corresponds to a diameter measurement on the ACR phantom of ±2 mm and a length measurement of ±1.5 mm. Thus, geometric accuracy measurements on the ACR MRI accreditation phantom, when measured over a 25-cm FOV (large phantom) and a 10-cm FOV (small phantom), are generally considered acceptable if they are within ±2 mm of the true values.

Gradient amplifiers need time to warm up and stabilize when they are turned on. Some sites power off their scanner hardware, including gradient amplifiers, overnight. Those sites should ensure that their hardware has been on at least an hour before images of the phantom are acquired.

Another factor leading to failure is the use of a very low MRI receiver bandwidth. It is common practice on some scanners and at some facilities to reduce receiver bandwidth to increase SNR. This strategy can be pushed to the point that normal inhomogeneities in the magnetic field (B0) manifest themselves as large spatial distortions in the image. On most scanners, the default bandwidth for T1-weighted acquisitions is set high enough to avoid this problem. If the geometric accuracy test exceeds the action limits and the ACR T1-weighted series (MRI Technologist’s Section, IV.C) was acquired at low bandwidth, one should try to acquire the images again at a larger bandwidth to see if the problem is eliminated.

B0 field inhomogeneities could be caused by improper adjustment of the gradient offsets, improper adjustment of passive and/or active magnet shims, or ferromagnetic objects such as a pocket knife or large hair clip lodged in the magnet bore. Especially on low-field magnet systems, which have relatively small volumes of gradient linearity and B0 homogeneity, it is possible that abnormally high B0 field inhomogeneities could cause significant dimensional errors in the phantom images. The service engineer should measure the homogeneity of the magnet periodically, and any inhomogeneity large enough to cause failure of the geometric accuracy test should be corrected (see Section IV.A).

Depending on the mix of studies at a given site, the qualified medical physicist/MRI scientist may determine that a more strict action limit should be put in place. Geometric accuracy is of particular interest in the following situations:

1. MRI images used for stereotactic surgical or radiation therapy planning

2. Assessment of the geometrical reproducibility of pulse sequences that use extremely high-gradient amplitudes and/or switching rates (e.g., EPI)

3. Co-registration of images acquired at various time points and/or from multiple scanners

If these types of studies are performed regularly on a given system, the qualified medical physicist/MRI scientist may decide that the volume geometric linearity should be checked much more often than annually. For measurements pertinent to radiation oncology, the radiation oncology physicist in charge of the procedure should be consulted to determine the most appropriate frequency for this test (Moerland et al [17]).

Spatial linearity measurements should also be performed on filmed images to provide combined performance information about the MR imager as well as the video and filming systems. For more information on volume geometric accuracy measurements, see Bakker et al [18].

4. High-Contrast Spatial Resolution

The origin of any detectable changes in high-contrast spatial resolution should be determined. Inappropriate filtering of the MRI signal may result in these types of changes. If high-contrast resolution is significantly degraded, check to make sure that any user-selectable spatial image filtering is turned off.

Poor eddy current compensation can cause failure. The scanner’s service engineer should check and adjust the eddy current compensation if this problem is suspected. Geometric errors from gradient miscalibration, B0 inhomogeneity and low acquisition bandwidth also can cause failure of this test. This problem also can arise if a gradient power supply becomes unstable.

With a field-of-view (FOV) of 250 mm using a 256 × 256 matrix size for the large phantom and a FOV of 120 mm using a 152 × 192 matrix size for the small phantom, scanners should be able to resolve the 1-mm hole pattern for the large phantom and the 0.8-mm hole pattern for the small phantom.

5. Low-Contrast Detectability (LCD)

Most scanners should be able to display at least nine spokes of holes out of 40 available spokes in slices 8–11 with the large phantom or at least nine spokes out of 20 available spokes in slices 6–7 with the small phantom for MRI systems with field strengths less than 3T using the ACR T1-weighted axial scanning protocol (see Phantom Test Guidance for the ACR MRI Accreditation Program [10]). For MRI systems with field strengths of 3T, scanners should be able to display at least 37 spokes out of the 40 available spokes in slices 8–11 for the large phantom. Typical LCD performance as a function of field strength is shown in Table 1. Slight changes in the number of spokes detected may arise due to slice-positioning errors, intermittent ghosting, or phantom tilting. The qualified medical physicist/MRI scientist should determine the minimum number of spokes perceived that constitute the action limit. Typically, a reduction of more than three spokes perceived would be cause for concern, indicating that the test should be repeated after positioning is checked.

The number of spokes visualized should be recorded weekly in a log for trend analysis. The qualified medical physicist/MRI scientist sets the action level based on a statistical analysis of a set of baseline data obtained from the specific MRI system. It is important to ensure that the technologist(s) are reproducibly positioning the phantom and prescribing the slice locations.

If slice positioning is accurate, changes in the number of spokes visualized may be due to a change in the SNR. If the SNR change is acceptable, then it will be necessary to establish new action limits. Acquire weekly LCD data and record them on a new Data Form for Weekly MRI Equipment Quality Control (MRI Technologist’s Section, VIII.A). Make a note of the change in the QC notebook (MRI Technologist’s Section, III.C) explaining the problem and actions taken. Proceed with patient scanning, starting with a fresh Data Form for Weekly MRI Equipment Quality Control (MRI Technologist’s Section, VIII.A).

Use the Data Form for Weekly MRI Equipment Quality Control (MRI Technologist’s Section, VIII.A) for the next 10 days as the baseline data for the new LCD action criteria. During that time, before the new criteria are set, monitor the SNR values (Section IV.D) and treat unusually large fluctuations or drift in the values as equivalent to a failure of the action criteria.

If the problem cannot be corrected immediately, consult with the supervising radiologist to determine whether patient scanning can proceed.

6. Artifact Evaluation

Common image artifacts noted on phantom images include the following:

• Gross geometric distortion

• Ghost images

• Line or pixels with unusually high and/or low intensities

• Receiver saturation errors

• Inappropriate image blurring or enhanced truncation artifact

Gross geometric distortion can occur even on a system that passes the geometric accuracy test because geometric accuracy measurements, as prescribed in the MRI Technologist’s Section, are only along the primary axes of the phantom. This problem is discussed in the MRI Technologist’s Section IV.C geometric accuracy and the references cited therein.

Ghost images present as low signal intensity representations of structures in the MR image that are shifted in the phase-encoding direction. The “ghosts” can be due to poor RF connections or motion. They are discussed in greater detail below in Section IV.D, Radiofrequency Coil Checks.

Lines or pixels with unusually high and/or low intensities can occur through several processes:

1. Bright lines can result from DC offsets on the MRI signal, especially on images with no signal averaging. Typically view-to-view phase alternation allows these artifacts to be located off to the side of the image and do not affect the utility of the image. A less frequent source of bright-line artifacts is an imperfect 180° pulse in a spin-echo acquisition. The position of the resulting artifactual line depends on the value of the read-out gradient and therefore can affect clinical image quality. Interference from external sources of RF can cause linear “single frequency” or broadband artifacts.

2. Zipper artifacts can be caused in a spin-echo sequence due to transverse magnetization being produced by imperfect slice excitation of the 180° refocusing pulse. The signal is constant from phase-encoding view to phase-encoding view so that it presents as a single frequency line of alternating intensity on the image.

3. DC-offset errors also can appear as a single bright pixel (sometimes as a dark pixel if overflow or image processing has occurred) at the center of the image matrix. They are due to improper scaling of low-frequency components (typically DC) in the Fourier transformation of the NMR time-domain signal.

4. Dotted-line artifacts across the image in the phase-encoding direction may be due to RF interference. If such artifacts are noted, one should check the integrity of the RF room shielding or identify the source of the RF interference, such as equipment or lighting within the MRI scan room.

If the RF attenuation (or gain) is not set correctly during the prescan, the signals acquired during one or more phase-encoding steps during image signal acquisition could be larger than the maximum allowable digitization step. This “saturates” the receiver so that the signal is not accurately digitized and the image is not properly displayed following the inverse Fourier transform. This image appears to have a very bright background that is smooth, not speckled like random noise. Spike signals that can be caused by malfunctioning electronics also can produce this type of artifact.

Inappropriate image blurring or enhanced truncation artifacts can be caused by excessive filtration. Use of zero-fill interpolation or filters that enhance spatial resolution tends to cause truncation artifacts to become more apparent. In contrast, filters that enhance SNR tend to result in increased image blurring.

The facility’s MRI Quality Assurance Procedures Manual (Radiologist’s Section IV.E) should state that any noticeable artifacts need to be brought to the attention of the service engineer and the qualified medical physicist or MRI scientist. The qualified medical physicist/MRI scientist must determine how often and for what duration an image artifact must appear in order for it to be significant enough to be worthy of investigation.

Artifacts can be very transient phenomena. When artifacts are noted, record any ancillary conditions that may be different from normal procedures. These data can be helpful to determine possible artifact sources. It is also good policy for the technologist to save the raw data of images in which artifacts occur. If the raw image data are accessible, they can aid in the diagnosis of artifact sources by noting the characteristics of the artifacts in k-space. For more detailed information on various MRI artifacts see Vlaardingerbroek and den Boer and Haacke et al.

A. Magnetic Field Homogeneity

- Objective

Homogeneity refers to the uniformity of the main magnetic field strength B0 over a designated volume. Magnetic field inhomogeneity is usually specified in parts per million (ppm) of the magnetic field strength over a spherical volume (DSV=diameter of spherical volume). The actual homogeneity will be influenced by a variety of factors, including imperfections in the magnet manufacturing, the degree to which the B0 magnetic field is perturbed by external ferromagnetic structures or, in the case of clinical scans, the presence of the patient within the field and the degree to which the above influences can be compensated using magnetic fields produced by shim and/or gradient coils. The most common problem caused by magnet inhomogeneities at high field strength is difficulty in obtaining uniform fat suppression. Inhomogeneities also can contribute to geometrical distortion of images (particularly at low field strengths), adversely influence image signal uniformity, increase the severity of wrap artifacts, and compromise SNR in some fast imaging sequences.

This is sometimes a difficult test to perform independently. If the magnetic field homogeneity test cannot be performed, the physicist should note this in the report, and the facility must arrange for the service engineer to provide the medical physicist/MRI scientist with a copy of the most recent field map, which should be filed as an attachment to the report. Test results should demonstrate that magnetic field homogeneity is within manufacturer’s specifications and was performed within the last six months. If the medical physicist/MRI scientist has an alternate method of accurately assessing magnetic field uniformity, it is acceptable, providing the report includes a description of the methodology used.

- General Theory

If a magnet is perfectly homogeneous over the imaging volume, all of the water protons (also referred to as spins) will precess at the same frequency, the magnet center frequency, which is directly proportional to the strength of the magnet. After applying an RF excitation pulse, and in the absence of any imaging gradients, a Fourier transform (FT) of the resulting signal will exhibit a strong, narrow peak at that center frequency. If the magnet were perfectly homogeneous, one would expect the FT to have a peak at only one frequency (i.e., be a delta function). However, random spin-spin interactions temporarily cause some protons to precess a little faster than the center frequency, whereas others will temporarily precess more slowly. This results in spreading of the peak with the full-width half-maximum (FWHM) of the frequency peak related to the average T2 time constant. A long T2 will have a narrow peak (little spin-spin interaction), and a short T2 will have a very broad peak (substantial spin-spin interaction). Along with these random spin-spin interactions, anything that causes imperfections in the static magnetic field will cause this spectral peak to spread. The greater the imperfections and the more inhomogeneous the magnetic field, the wider the peak. Although it is quick and easy to perform, monitoring the spread of the spectral peak is a crude and insensitive method of assessing magnet homogeneity. This measurement contains no information regarding spatial variations of the magnetic field.

Gradient-echo (GRE) imaging techniques can be used to obtain spatial information about the magnetic field. (Spin-echo techniques cannot be used because the 180° pulse used to generate the spin-echo reverses and eliminates any effect of magnetic field inhomogeneities.) Ignoring T2 effects, if a magnet is perfectly homogeneous, then at the time of a gradient echo, all of the spins would be completely in phase with each other. As stated above, spatial variations of the magnetic field will cause spins in different parts of the FOV to spin a little faster or a little slower, causing the slower spins to lag behind the spins at the center frequency and the faster ones to run ahead of the spins at the center frequency. The greater the difference in the magnetic field across the phantom volume, the greater the differences in the spin frequencies and the greater the spread of the phases of the spins at the echo time. The differences in phases of the spins measured by a gradient echo are linearly proportional to the differences in frequencies (hence, linearly proportional to the differences in magnetic field) and linearly proportional to the echo time. An echo time of 10 ms corresponds to a frequency of 100 Hz (1/0.010 seconds) per phase cycle. A spin that precesses 25 Hz faster or slower than the center frequency will be π/2 radians (90°) out of phase with the center frequency spins. If a TE of 20 ms is used, the spins have twice as long to dephase, so they will be π radians (180°) out of phase.

Reconstructing phase images, as opposed to the more common magnitude images, provides a map of the differences in precessional frequencies relative to the center frequency and therefore a map of the changes in the magnetic field. The drawback of the phase map method is that differences in the magnetic field are not the only causes of spatial variation of phase. If the echo peak is not exactly at the center of the sample window, it will cause a linear phase ramp across the FOV. At higher field strengths, the RF does not penetrate water-filled phantoms as well as at low fields. These RF penetration differences, as well as magnetic susceptibility differences, result in changes in the phase of the received signal that vary by distance from the surface of the phantom. Problems with the RF receiver chain can also result in phase variations. Because of all of these other sources of phase variation, phase map images only provide an upper limit on the frequency or magnetic field variation across the FOV; the true variation will be lower.

With the exception of phase differences caused by magnet field inhomogeneities, most of these other phase variations are not affected by changes in echo time. These other phase variations can be removed by acquiring two GRE images, reconstructing phase maps, and then subtracting the two phase-map images. The resulting phase differences will be proportional only to the magnetic field variations and to the difference in echo times. For example, if echo times of 10 and 15 ms are used, the resulting difference of 5 ms corresponds to 200 Hz per phase cycle. A phase shift of 90°, or one-quarter of a cycle, would mean there is a 50 Hz difference in the resonance frequency. If this were the peak-to-peak difference across the DSV at 1.5T, then the magnetic field inhomogeneity would be reported as 50 Hz/64 MHz (the center frequency at 1.5T) or 0.78 ppm. The phase-difference method can be performed using either 2-D or 3-D GRE sequences and provides the most accurate measurement of magnetic field homogeneity.

Four different methods are presented: the spectral peak method, the bandwidth-difference method, the phase-map method (using GRE phase maps acquired at a single TE value), and the phase-difference method (subtraction of GRE phase maps acquired at two different TE values).

1. Spectral Peak Option

- Test Procedure

1. Position a uniform, spherical phantom at the center of the magnet. The phantom should have a spherical volume diameter similar to that cited by the manufacturer’s homogeneity specifications.

2. Obtain a spectrum from the sample. This can often be accomplished even without special spectroscopy software by going into manual tuning or prescan mode. Ensure that the frequency resolution is much less than the expected peak width.

- Data Interpretation & Analysis

1. Measure the FWHM of the spectral peak. Convert the FWHM from Hz to ppm of the B0 field strength (in Tesla) using the Larmor equation:

FWHM(ppm) = FWHM(Hz)/42.576B0(T)

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

2. BANDWIDTH-DIFFERENCE OPTION

- Test Procedure

An additional method for determining field homogeneity has been described by Chen et al [21]. This method is of particular value when assessing systems that do not provide access to either phase images or a detailed frequency plot. The bandwidth-difference method makes use of the fact that spatial distortions are a function of field homogeneity and gradient strength. Since for a given FOV in the frequency-encoding direction (FOVx) the frequency-encoding gradient strength (Gx) is a function of receiver bandwidth (BWx), it is possible to estimate field homogeneity (ΔB0) by comparing the spatial distortion (d1 - d2) observed at the same FOVx for both small (BW1) and large (BW2) bandwidth acquisitions (Figure 1). The following equation is used for estimating the magnetic field inhomogeneity in ppm, using the bandwidth-difference option:

∆B0 (ppm)= (BW1 x BW2) x (d1 - d2) / 42.576MHz/T x B0(T) x FOVx X (BW2 - BW1), where

BW1 = smallest available receiver bandwidth (Hz)

BW2 = largest available receiver bandwidth (Hz)

(d1 - d2) = spatial distortion (mm) measured as the distance difference of corresponding points in the phantom in the frequency-encoding direction for a specified DSV

FOVx = FOV in the frequency-encoding direction (mm)

In the above equation, the receiver bandwidth must be expressed in units of Hz across the full FOV. However, it should be noted that vendors may express the receiver bandwidth in different ways. For example, some vendors display receiver bandwidth as half the frequency shift across the full FOV, which requires doubling the displayed receiver bandwidth. Bandwidth may also be expressed as either Hz/pixel or as the fat-water-shift (FWS) expressed in units of pixels.

To convert pixel bandwidth (Hz/pixel) to receiver bandwidth (Hz), it is necessary to multiply the Hz/pixel value for the image by the number of pixels in the frequency-encoding direction. Note that the displayed image matrix may differ from the acquisition matrix when image interpolation is used. Most manufacturers quote pixel bandwidth in the acquired image, but at least one manufacturer quotes pixel bandwidth in Hz per displayed pixel when image interpolation is used.

For example, if the image bandwidth per pixel is 125 Hz/pixel, and the image matrix is 256 x 256, the receiver bandwidth (BW) for the full FOV in Hz is calculated with the following formula:

BW (Hz) = 125 Hz/pixel × 256 pixels = 32,000 Hz

To convert FWS expressed in units of pixels to Hz, it is necessary to first determine the static field strength of the system being evaluated and then determine the nominal frequency difference between fat and water (FD) for that field strength. FD is commonly assumed to be approximately 3.5 ppm. Assuming resonant frequencies of 63 MHz and 127 MHz for 1.5T and 3T systems, respectively, the applicable FD values are estimated as follows:

at 1.5T: FD(Hz) = 3.5 ppm × 63 Hz/pixel = 220 Hz

at 3.0T: FD(Hz) = 3.5 ppm × 127 Hz/pixel = 440 Hz

The BW is then determined by multiplying the applicable FD (in Hz) by the number of acquired image pixels in the frequency-encoding direction and then dividing by fat-water shift (in pixels).

For example, if the stated fat-water shift is 1.75 pixels for an image with a 256 × 256 matrix and field strength of 1.5T, the BW (Hz) would be determined as follows:

BW(Hz) = 220Hz × 256 pixels / 1.75 pixels = 32,183Hz

The bandwidth-difference method assesses field homogeneity only in the direction of the frequency-encoding axis. Thus, to assess field homogeneity over the desired DSV, it will be necessary for separate images to be acquired with the frequency-encoding direction along all three orthogonal axes.

1. Position the phantom in the center of the RF coil. The size of the phantom should be appropriate for the DSV to be assessed. A spherical phantom with identifiable reference points is recommended. A right cylinder also can be used, but ideally the cylinder should have a length that is greater than twice the diameter, otherwise the measurements may be subject to susceptibility artifacts. Employ a simple, field-echo (spoiled GRE) pulse sequence. A spin-echo sequence may also be used for this test to increase SNR but will require longer acquisition times. It should be noted that using a larger acquisition matrix will increase precision of the measurement by reducing the pixel size and thereby reducing the uncertainty in the distance measurements. Ideally a large matrix value in the frequency-encoding direction should be used (e.g., 512).

2. Acquire three separate series, each series consisting of a single image through the center of the phantom, with receiver bandwidth BW1, one with the frequency-encoding oriented along each of the three orthogonal axes. Acquire three more separate series, each consisting of a single image, with receiver bandwidth BW2, one with frequency-encoding along each of the three orthogonal axes while maintaining the phantom position and all other acquisition parameters besides BW the same as used in Step 1 above.

3. If a right cylinder is used, it will be necessary to acquire BW1 and BW2 images in each orthogonal plane before repositioning the phantom to assess all three planes.

- Data Interpretation & Analysis

1. Images acquired with two different bandwidths but at corresponding slice locations throughout the DSV will be compared. First, display an image acquired at BW1. Choose two reference points in the image that extend the full length of the desired DSV to be assessed, e.g., points A and B in Figure 1. Magnify the image on the monitor by a factor of two to four.

2. Adjust the display window using a narrow window width, keeping the reference points to be measured in the image clearly visible. The display level should then be set to a level roughly one-half that of the signal in the bright portions of the phantom.

3. Use the viewer’s length measurement tool to determine the distance between the two points. Record the measured length (mm) as “d1.”

4. Repeat Steps 1–3 for the same reference points and corresponding slice position acquired with bandwidth BW2. Record the measured length (mm) as “d2.” It should be noted that it is important to identify the same physical reference points in each of the two images. Otherwise, an additional unknown uncertainty in the measurement will be introduced.

5. Record the distance difference (d1 - d2) for that plane and slice location.

6. Repeat this procedure (Steps 1–5) to obtain the distance difference for the other planes and slice locations throughout the volume.

7. Using the maximum distance difference measured above, determine the greatest value of ∆B0 using the equation above for each orientation. This value is the inhomogeneity (in ppm) for the specified diameter.

3. PHASE MAP OPTION

- Test Procedure

This test provides an accurate upper bound measurement of B0 inhomogeneity using a uniformity phantom (Figure 2). However, the test requires features of the MRI system (i.e., display of phase images), which may not be available on all units. If the MRI system can display phase-contrast images, a pixel-by-pixel measurement of field inhomogeneity can be obtained.

Phase-contrast images may display phase wrap in those regions where the total phase angle exceeds ±180° from the reference phase. Although unwrapping algorithms can be employed to eliminate this complication, this feature typically must be performed offline on an independent workstation.

1. Position a uniform phantom in the center of the magnet. The size of the phantom should be appropriate for the diameter to be assessed and, in general, the larger the better. A spherical phantom is preferable, if available. Employ a field-echo (a spoiled GRE, either 2-D or 3-D) pulse sequence with the appropriate TE (see below). Do not use a spin-echo sequence because it will result in rephasing of the phase differences caused by magnetic field inhomogeneities.

2. In theory, nearly any echo time can be used, but some echo times simplify processing. A TE of 10 ms corresponds to 100 Hz per phase cycle, and 20 ms corresponds to 50 Hz per phase cycle. The longer the TE, the greater the sensitivity, but this also potentially results in a greater number of phase wraps that must be dealt with and a reduction in the SNR. Another approach is to choose a TE that corresponds to an integer value of ppm inhomogeneity. At 1.5T, the center frequency is approximately 64 MHz. One ppm per phase cycle would be 64 Hz, which corresponds to a TE of 15.6 ms.

3. Acquire a set of GRE images. A 3-D set acquired on a spherical phantom is best, since it permits evaluation of the complete volume from a single scan. If a 3-D scan is not possible, or if a nonspherical phantom is being used, then multiple slices should be obtained in each of the three orthogonal plane directions.

When using a 3-D GRE (or spoiled gradient-recalled [SPGR]) sequence, typical scan parameters would be a TR of 40–50 ms, TE of 10–20 ms, flip angle of 30–40°, and a 128 x 128 x 64 matrix. The FOV should be 10–25% larger than the diameter of the phantom, and the excited slab should be roughly the same size as the FOV, allowing for easy multiplanar reformatting.

When using a 2-D GRE (or SPGR), typical scan parameters would be a TR of at least 200 ms and long enough to acquire all of the desired slices in one TR period. The TE could be 10–30+ ms, as appropriate. Matrix size is not critical; 128 × 128 or 128 × 64 is reasonable. Use a slice thickness of 5 mm (high field) to 10 mm (low field). The number of slices depends on the size and shape of the phantom.

Data analysis involves assessing the maximum phase shift over the entire phantom. As illustrated below, the maximum phase shift could occur between any two points in the phantom (e.g., center-to-edge, edge-to-edge, and not necessarily through the center of the image).

Each vendor has its own way of displaying and scaling phase images. Some will display the pixel value as the phase in radians times 1000. Others will scale from -2048 to +2048, or -5000 to +5000, or 0 to 4096; there is no standard. The first task of the physicist using this technique is to determine how the images are scaled. Unfortunately, it is not always easy to do. Figure 2a shows a phase map obtained from a 3T scanner using a 32-cm diameter water-filled spherical phantom containing NiCl. The figure shows the phase map of the center slice of a 3-D volume. There is an obvious phase wrap at the point labelled B and all along that circular border. By moving an ROI around that border, it is possible to determine the largest and smallest pixel values and assign those as ±π or ±180°. In theory, this is reasonably straightforward. However, some vendors will calculate the phase images and then apply filters that can round off transitions or enhance edges, but this method should provide acceptable results. See the phase-difference method section for an alternative method, IV.A.4.