ACR®
AMERICAN COLLEGE OF RADIOLOGY

QUALITY IS OUR IMAGE

2015
Magnetic Resonance Imaging

QUALITY CONTROL MANUAL

Radiologist's Section

MRI Technologist's Section

Medical Physicist/MRI Scientist's Section

ACR®
AMERICAN COLLEGE OF RADIOLOGY

QUALITY IS OUR IMAGE

2015
Magnetic Resonance Imaging

QUALITY CONTROL MANUAL

Radiologist's Section
MRI Technologist's Section
Medical Physicist/MRI Scientist's Section

American College of Radiology
Committee on Quality Assurance in Magnetic Resonance Imaging

Ron Price, PhD, FACR, chairman
Jerry Allison, PhD, FACR
Geoffrey Clarke, PhD, FACR
Michael Dennis, PhD
R. Edward Hendrick, PhD, FACR
Carl Keener, PhD
Jeff Masten, MS
Moriel Nessaiver, PhD
Joe Och, MS
Donna Reeve, MS

Priscilla Butler, MS, ACR Staff Member
Dina Hernandez, RT, ACR Staff Member
Leonard Lucey, JD, ACR Staff Member
Pam Wilcox, MBA, ACR Staff Member

Contents

PREFACE

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.

Anthony Scuderi, M.D.

Chairman, ACR Committee on MRI Accreditation

ACR®
AMERICAN COLLEGE OF RADIOLOGY

QUALITY IS OUR IMAGE

2015
Magnetic Resonance Imaging

QUALITY CONTROL MANUAL

Radiologist's Section

Contents

REVISIONS

Date	Page(s)	Section	Description of Revisions

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.

DEFINITIONS

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.

RADIOLOGISTS' RESPONSIBILITIES

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 modality

Procedures 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.

E. MRI Quality Assurance Procedures Manual

Working as a team, the radiologist, QC technologist, and qualified medical physicist or MRI scientist should develop and follow an MRI QA procedures manual that is available to all members of the staff. The QC testing described in this ACR QC Manual should be a central part of the site's QA procedures manual.

In addition, the site's procedures manual should contain:

1. Clearly assigned responsibilities and clearly developed procedures for QA/QC testing

2. Records of the most recent QC tests performed by the QC technologist and qualified medical physicist or MRI scientist

3. A description of the orientation program for operators of MRI equipment, including its duration and content

4. Procedures for proper use and maintenance of equipment

5. MRI techniques to be used, including pertinent information on positioning, coils, pulse sequences, and contrast agent administration

6. Precautions to protect the patient and equipment from potential hazards associated with the strong static magnetic, pulsed magnetic field gradients, and RF fields associated with MRI

7. Proper maintenance of records, including records of QC and QA testing, equipment service and maintenance, and QA meetings
8. Procedures for the cleaning and disinfection of MRI systems and ancillary equipment

OTHER PROFESSIONALS' RESPONSIBILITIES

A. The Responsibilities of the Qualified Medical Physicist or MRI Scientist

The responsibilities of the qualified medical physicist or MRI scientist relate to equipment performance, including image quality and patient safety. An MRI equipment performance review should take place at the time the equipment is commissioned and at least annually thereafter. The qualified medical physicist/MRI scientist shall repeat appropriate tests after major repair or upgrade to the MRI system.

Specific tests include the following:

1. Magnetic field homogeneity evaluation
2. Slice-position accuracy
3. Slice-thickness accuracy
4. RF coil checks, including signal-to-noise ratio and image intensity uniformity of volume coils
5. Soft-copy (monitors) QC
6. MR safety program assessment

B. Baseline Measurements and Action Limits

The qualified medical physicist or MRI scientist is responsible for running baseline QC measurements. The qualified medical physicist or MRI scientist establishes performance criteria for the technologist's QC program. This applies specifically to the determination of "action limits," which are the values of specific parameters obtained from the QC tests at which service is requested to address a particular problem in image quality.

During the annual review, the qualified medical physicist or MRI scientist also examines the records of the weekly QC tasks performed by the QC technologist(s). Following this review and the completion of the tests listed above, recommendations may be made regarding improvements in equipment performance or improvements in the QC process.

C. Purchase Specifications and Acceptance Testing

Many manufacturers sell MRI systems with a large variety of features and a wide range of prices. The quality of available units varies, but due to its complexity an MRI system's quality may be difficult to discern before the purchase.

The quality of new equipment can be ensured through the use of purchase specifications. Purchase specifications also describe to vendors the type of equipment that is desired by the purchaser. Purchase specifications usually require vendors to provide detailed technical and performance specifications to the purchaser prior to the selection of equipment. These

vendor-provided specifications can then be used to help determine the equipment to be purchased and provide a set of quantitative performance specifications to be compared with measurements on the MRI equipment during acceptance testing.

The purchase should be made contingent on satisfactory performance during acceptance testing. Acceptance testing is more rigorous than the QC program detailed here and should be conducted by an experienced medical physicist or MRI scientist. The QC program described in this manual can provide a minimum set of acceptance tests but is intended primarily to document consistency of performance after the unit has been accepted and put into service.

Once acceptance testing has been completed, there must be adequate applications training for the entire MR staff.

D. MRI QC Technologist's Responsibilities

The MRI QC technologist's responsibilities revolve around image quality. More specifically, the functions performed by the technologist that affect image quality are patient positioning, image production, image archiving, and film processing.

The specific weekly QC procedures to be conducted by the radiological technologist include the following:

1. Setup and table position accuracy
2. Center frequency
3. Transmitter gain or attenuation
4. Geometric accuracy measurements
5. High-contrast spatial resolution
6. Low-contrast detectability
7. Artifact evaluation
8. Film printer quality control (if applicable)
9. Visual checklist

Although it is written primarily for the QC technologist, the radiologist should read in detail Section III, Important Points, in the MRI Technologist's Section.

E. Quality Control of Hard-Copy and Soft-Copy Images

Image display QC is essential for accurate interpretation of MR images. If images are interpreted from film, the supervising radiologist should regularly review the MRI QC technologist's records on hard copy image QC. The interpreting radiologist should notice and call the MRI technologist's attention to image quality problems, including artifacts, whenever they occur.

If images are interpreted from film, radiologists should refer to the MRI Technologist's Section V, Film Printer Quality Control, and be thoroughly familiar with these procedures. Sensitometry should be performed and results plotted before patient images are printed for interpretation. The radiologist should be comfortable reviewing the results of sensitometric testing and should ensure that appropriate steps are taken when test results are outside of control limits.

It is more common for radiology departments and MRI clinics to obtain diagnoses from images displayed on review workstations with high-quality monitors. Proper viewing conditions and computer workstation monitor performance are essential in MRI, as in other areas of radiology. The radiologist should give particular attention to the information given in the Medical Physicist/MRI Scientist's Section IV.E.

CONCLUSION

In addition to this technical QC program, the MRI radiologist needs to be involved in an ongoing program to assess the quality of MRI interpretations. Procedures for interpretive QA are not addressed in this manual, but have been published in the radiological literature.

The public expects our profession to provide accurately interpreted MR images of the highest quality. Only a strong, consistent commitment to QA by all parties involved in performing MRI will validate that trust.

REFERENCES

A. Downloadable from ACR Website

- Magnetic Resonance Imaging Accreditation Program Requirements
- Breast Magnetic Resonance Imaging Accreditation Program Requirements
- Phantom Test Guidance for the ACR MRI Accreditation Program
- ACR-AAPM Technical Standard for Diagnostic Medical Physics Performance Monitoring of Magnetic Resonance Imaging (MRI) Equipment
- ACR Practice Parameter for Performing and Interpreting Magnetic Resonance Imaging (MRI)
- ACR Manual on Contrast Media, version 9, published 2013
- ACR MRI Terminology Glossary Resource

B. Other Publications

- Kanal E, Barkovich AJ, Bell C, et al. ACR guidance document on MR safe practices: 2013. *Journal of Magnetic Resonance Imaging*. 2013;37(3): 501-530.
- Gilk T, Kanal E. Interrelating sentinel event alert #38 with the ACR guidance document on MR safe practices: 2013. An MRI accreditation safety review tool. *Journal of Magnetic Resonance Imaging*. 2013;37(3):531-543.

ACR®
AMERICAN COLLEGE OF RADIOLOGY

QUALITY IS OUR IMAGE

2015
Magnetic Resonance Imaging

QUALITY CONTROL MANUAL

MRI Technologist's Section

Contents

Revisions

Date	Page(s)	Section	Description of Revisions

INTRODUCTION

A well-designed, well-documented, and reliably executed quality control (QC) program is essential to consistent production of high quality MR images. The American College of Radiology (ACR) has developed the material in this manual to assist radiologists, radiological technologists, and qualified medical physicists or magnetic resonance imaging (MRI) scientists in establishing and maintaining such QC programs. This is in accordance with the ACR's educational and patient service missions and in response to growing requests from the diagnostic imaging community for guidance on MRI QC [1,2].

This section of the manual describes the MRI technologist's duties in the QC program. At first glance, the careful and necessarily detailed descriptions may make it seem as if the technologist's part is complex and time-consuming, but that is not the case. It can be carried out with a minimal investment in time and equipment. In essence, the technologist's responsibilities include regularly performing a set of short QC procedures, recording the procedure results in a QC log, and initiating appropriate corrective actions as needed.

There are seven main parts to this section: Part II is this introduction. Part III discusses important points of general relevance, such as the QC log. Parts IV, V, and VI describe the individual QC procedures. Part VII is a list of useful references. Part VIII is an appendix, which contains examples of useful data forms.

Each procedure description follows the same format:

- Objective
- Frequency
- Required equipment
- Test procedure steps
- Data interpretation and corrective actions

Table 1 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.

IMPORTANT POINTS

A. Quality Control Testing Frequency

The technologist's QC testing procedure frequencies given in Table 1 and in the rest of this manual are the minimum recommended frequencies. However, we strongly recommend that the tests be done on a daily basis. If problems are detected often, if the equipment is unstable, or if the system has just been subject to a significant repair or upgrade, then it may be necessary to carry out some of the procedures more frequently.

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.

B. Designated Quality Control Technologist(s)

A QC technologist should be charged with the QC procedures for a particular piece of equipment. Using the same personnel leads to greater consistency in measurements and greater sensitivity to incipient problems. This does not mean that a single technologist must perform the QC on all devices. It is acceptable, and often convenient, to have different technologists responsible for QC on different devices. When the designated QC technologist for a given piece of equipment is not available, the QC procedures should still be carried out on schedule by a backup QC technologist. To ensure that the performance of QC tasks is not linked to specific personnel's work schedules, an adequate number of technologists should be trained in the QC procedures.

C. Quality Control Log

A QC log shall be maintained and the results of QC activities recorded in the log at the time they are performed. Blank forms for this purpose are provided in the appendix (Section VIII) for each of the procedures described in this section. These forms may be freely copied. Sites may also choose to develop their own forms.

The content of the QC log will vary between facilities, depending on their size, administrative organization, and the preferences of the QC team. Small facilities may have a single log encompassing all of their equipment; large facilities will often have separate logs for equipment at separate locations. In general, the QC log should have the following:

1. A section describing the facility's QC policies and procedures for the equipment covered by the log
2. A section of data forms where QC procedure results are recorded for each piece of equipment covered by the log
3. A section for recording notes on QC problems and corrective actions

The QC log shall be kept in a location accessible to, and known to, all members of the QC team and the service engineer, so that they may refer to it when questions arise. The section of the log for recording QC problems and corrective actions can facilitate communications between the service engineer and QC team members who often have different work schedules.

D. Quality Control Data Review

The QC log data will be reviewed at least annually by the qualified medical physicist/MRI scientist and/or supervising radiologist. The purpose of the review is to make sure no image quality problems have been inadvertently overlooked, and to verify that the QC procedures are being performed on schedule with at least the minimum recommended frequency. It is recommended that this review be part of a Quality Assurance Committee meeting (Radiologist's Section III.B).

E. Alternative Phantoms

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 QC using either of the two phantoms. A committee of MRI physicists and radiologists designed the ACR phantoms with the goals of producing effective, versatile, and economical MRI system tests. The ACR phantom is mandatory for application to the accreditation program, so all accredited sites will already have one. The procedures described here for weekly QC were written specifically for the ACR phantoms. The decision to use an alternative phantom should be made by the qualified MRI physicist/scientist.

Alternative phantoms should only be used if they are capable of providing tests substantially equivalent to the ACR phantoms and after they have been reviewed and approved by a qualified medical physicist or MRI scientist. If this decision is made, then the physicist shall document the necessary procedures, analysis methods, and action criteria for the tests to be performed with the alternative phantom and provide the QC technologist training in these methods. The alternate test procedures should, at a minimum, provide QC parameters substantially equivalent to the procedures listed in Table 1.

F. Alternative Procedures

Test procedures enumerated in this document should be considered the minimum set of tests and should be used unless the recommended procedures are for some reason unavailable or not possible on a particular scanner. The details of alternative QC tests shall be described in detail and placed in the site's MRI QA Procedures Manual (Radiologist's Section IV.E).

Additional tests may be required if the system is used routinely for advanced clinical MRI procedures. Such studies would include, but are not limited to, imaging to obtain reference data for stereotactic therapeutic procedures, MR spectroscopy, cardiac MRI, diffusion-weighted and susceptibility-weighted MRI, MR elastography, functional MRI, MR-guided biopsy, and advanced angiographic and blood perfusion methods using contrast agents. Enumeration of QC tests for these advanced MRI applications is beyond the scope of this manual. The qualified medical physicist or MRI scientist is responsible for determining and setting up the methods and frequencies for these tests.

G. Action Limits

Performance criteria for the various QC measurements are specified in terms of action limits (also known as control limits), which define the range of acceptable values; outside of which corrective action is required. Suggested performance criteria are defined for each procedure. In some cases, the stability of the equipment and the consistency of the technologist's measurements may be such that the measured values are always well within the action limits. In those cases a tightening of the action limits may be useful for greater sensitivity to developing problems. It is the responsibility of the qualified medical physicist or MRI scientist to set the action criteria and verify that they are adequately sensitive to detect MRI equipment problems.

The qualified medical physicist or MRI scientist should write the action limits on the top line of the data form for the Weekly MRI Equipment Quality Control (Section VIII.A).

TECHNOLOGIST'S WEEKLY MRI QUALITY CONTROL

To ensure that the MR scanner is producing images of quality equal to that produced when the scanner is known to be functioning correctly, phantom image acquisition and analysis should be performed at least weekly. After these data are acquired, the technologist performs simple measurements to verify that system performance is within the action limits.

The ACR technologist's tests should be performed in addition to any testing required by the manufacturer. In contrast to the manufacturer's tests, which often involve automated analysis and storage of the QC data in directories unavailable to the technologist, the data-collection methods recommended here require that the technologist acquire and assess images at least weekly. These methods permit the QC technologist to identify and report poor MRI system performance at or near the time system degradation occurs.

Acceptance testing should take place before the first patient is scanned and after major repairs. Major repairs include replacement of or repair of the following subsystem components: gradient amplifiers, gradient coils, magnet, RF amplifier, digitizer boards, and 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).

Action limits are established by the qualified medical physicist/MRI scientist at the initiation of the weekly QC program in order to establish scanner-specific baseline values for the low-contrast detectability (LCD) and center frequency. Action limits should be reevaluated whenever there are hardware changes or service activities that alter the signal acquisition and excitation electronics.

The recommended weekly QC scanning series is the same sagittal localizer and axial T1-weighted sequence as acquired for the ACR MRI Accreditation Program. The following specific documents are available from the ACR website (www.acr.org):

- Site Scanning Instructions for Use of the MR Phantom for the ACR MRI Accreditation Program
- Site Scanning Instructions for the Use of the Small MR Phantom for the ACR MRI Accreditation Program
- Phantom Test Guidance for the ACR MRI Accreditation Program
- Phantom Test Guidance for Use of the Small MRI Phantom for the ACR MRI Accreditation Program

The weekly QC procedure is organized into three parts:

1. Position the large phantom in the head coil or, for extremity MRI systems, position the small phantom in the knee coil. Use the computer interface to set up scanning and identify the patient as a phantom.
2. Record center frequency and transmitter attenuation (or transmitter gain).

3. Analyze the images after scanning. Measure the phantom dimensions. Assess high-contrast resolution and LCD. Note image artifacts.

A. Setup and 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).

TEST PROCEDURE

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.

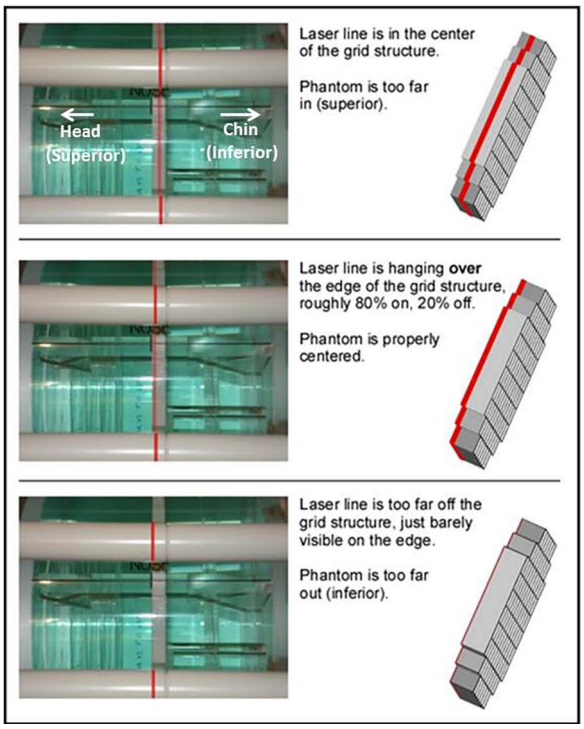


Figure 1. Illustration of the use of the central grid structure for alignment of the large phantom when the head coil has a central bar that blocks visualization of the small cross-line positioning marker. The phantom is properly positioned when the laser light is aligned with the superior (head direction) edge of the grid structure. If the laser light is accurately aligned, the phantom will be correctly positioned at the magnet isocenter after moving the phantom 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.

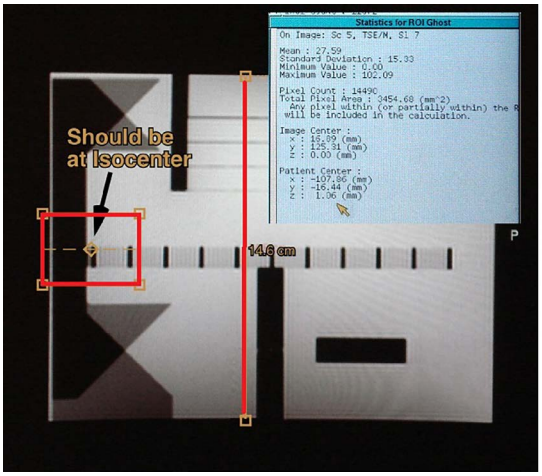
2. The ACR sagittal localizer sequence should use the following parameters:

   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).

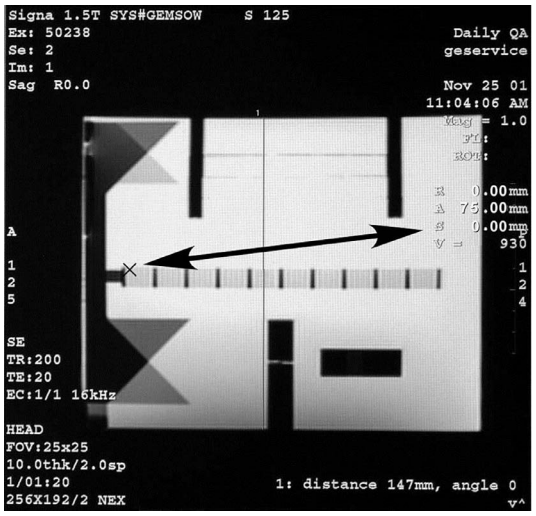
   For the small phantom: 1 slice, sagittal spin-echo, TR=200 ms, TE=20 ms, slice thickness=20 mm, FOV=12 cm, matrix=152 × 192, NEX=1, scan time: 32 s. If the 20-mm thick slice causes artifacts, a 10-mm slice may be used.

DATA INTERPRETATION AND 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).



a.



b.

Figure 2. a) An example taken from a scanner where a square ROI has been placed with its center on the anterior/superior edge of the grid, exactly where the laser was positioned. In this example, the z-coordinate is +1.06 mm (see data inset), which is acceptable because it is less than ±5 mm. b) An example taken from a scanner and showing the cursor on the superior edge of the grid is exactly at isocenter, SØ.ØØ mm; the S indicates distance from isocenter in the superior z-direction.

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

OBJECTIVE

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 (B_0). Changes in the B_0 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

REQUIRED EQUIPMENT

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).

TEST PROCEDURE

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 AND 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.

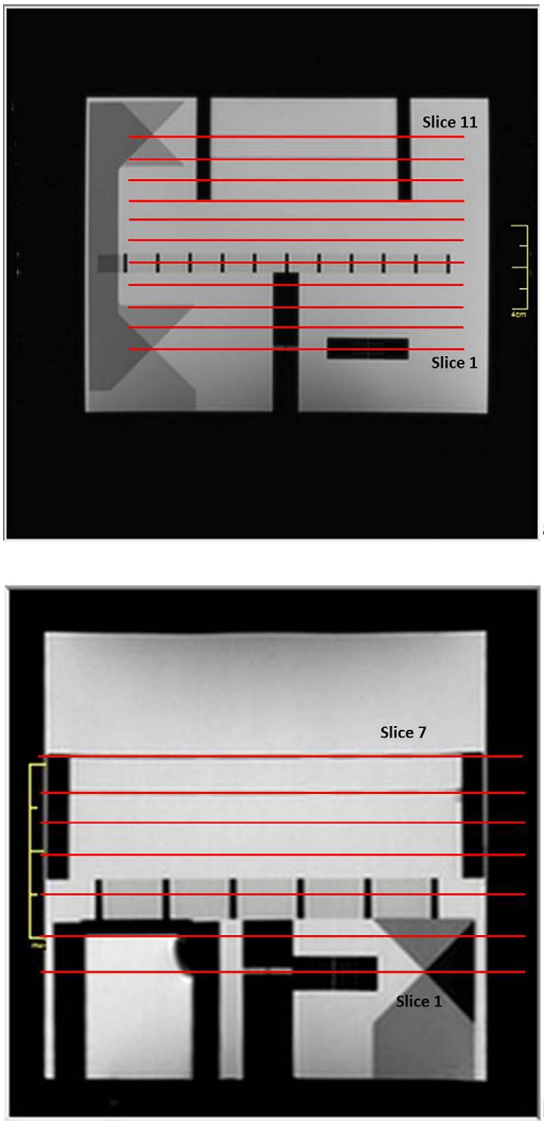


Figure 3. a) Sagittal image of ACR large phantom with positions of the 11 axial slices of the T1-weighted series superimposed. b) Sagittal image of ACR small phantom.

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

OBJECTIVE

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 AND 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

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

OBJECTIVE

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).

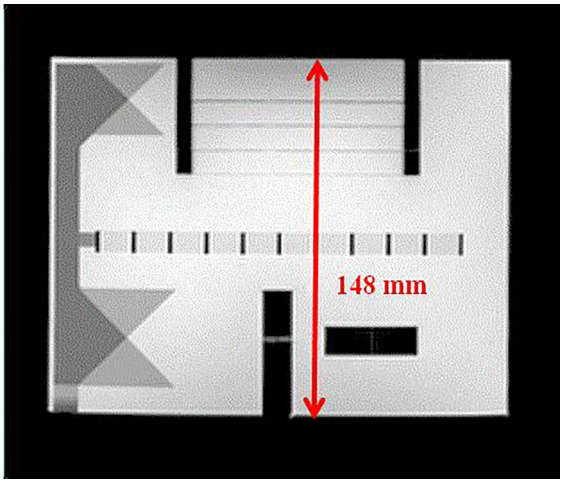


Figure 4. Positioning of length measurement on ACR MR accreditation phantom.

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).

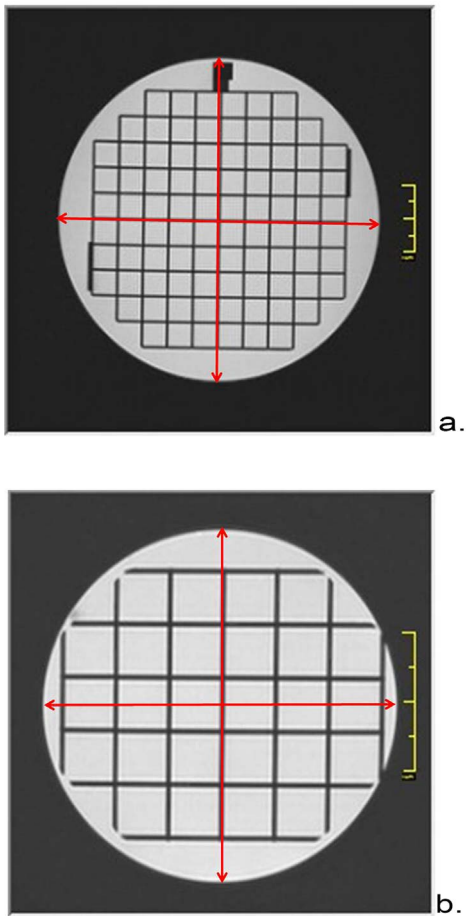


Figure 5. Position for x- and y-direction diameter measurements on ACR MRI accreditation phantom in the large phantom, slice 5 (a) and small phantom, slice 3 (b).

DATA INTERPRETATION AND 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.

B_0 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 B_0 homogeneity, it is possible that abnormally high B_0 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

OBJECTIVE

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.

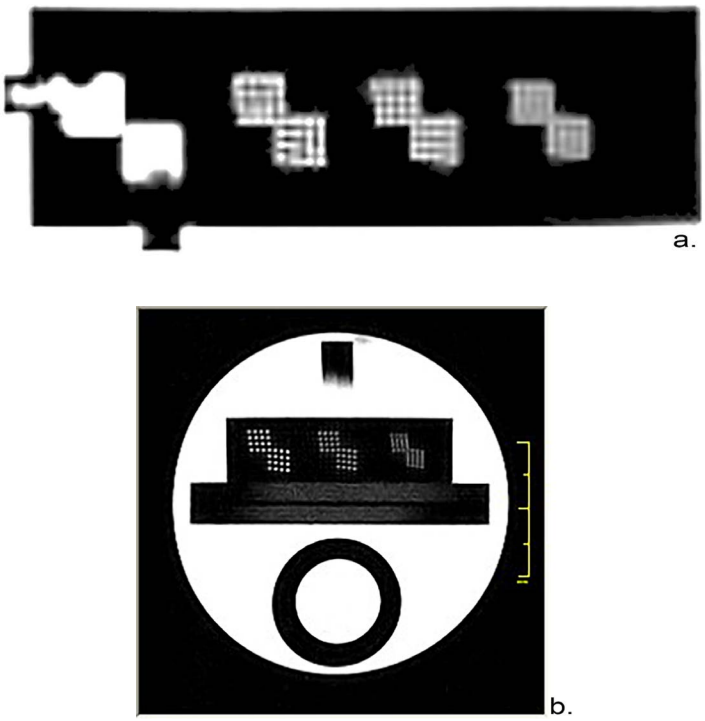


Figure 6. a) Large phantom high-contrast resolution insert from slice 1 of an axial series shows three sets of two arrays of holes. Hole sizes and spacing: from left, 1.1 mm, 1.0 mm, and 0.9 mm. b) Small phantom high-contrast resolution insert from slice 1. Hole sizes and spacing: from left, 0.9 mm, 0.8 mm, and 0.7 mm.

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 AND 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 (B_0) 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.

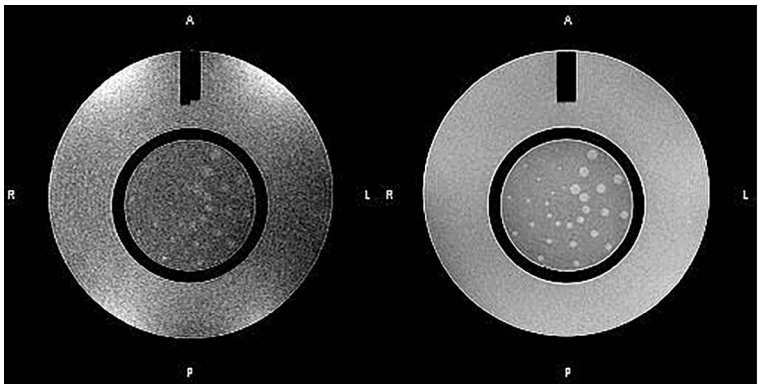
The ACR MRI accreditation phantom contains low-contrast objects of varying size and contrast that appear on four slices of the T1-weighted axial multislice series (Figure 7): 8 through 11 for the large phantom and 6 and 7 for the small phantom. In each slice the low-contrast objects appear as rows of 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.

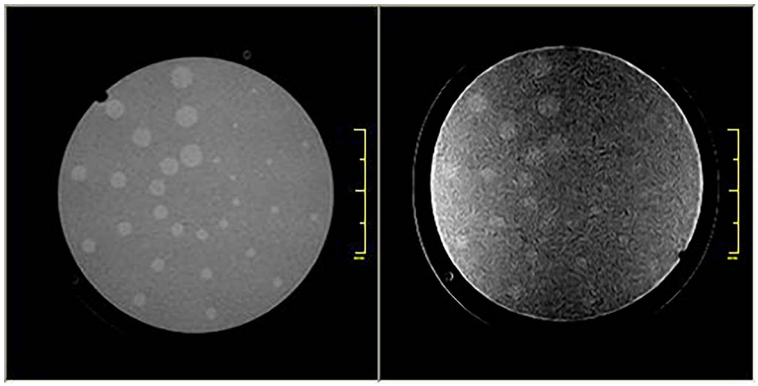
The low-contrast disks are actually holes drilled in thin sheets of plastic mounted in the phantom at the locations of the four slices. The contrast is derived from the displacement of solution from the slices by the plastic sheets.

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).



a



b.

Figure 7. Phantom images of low-contrast detectability (LCD) inserts. a) Large phantom LCD insert images. Slice 11 (5.1% contrast) acquired on two different scanners, each with proper slice positioning. The left image is from a 1.5T scanner where all 10 spokes (each spoke consisting of three test objects) are visible. Right image is from slice 11 of a 0.3T scanner where only seven complete spokes are visible. The qualified medical physicist or MRI scientist should designate the specific ACR MRI phantom image slice that is most appropriate to assess for weekly QC. b) Small phantom LCD insert images. The left image is slice 7 (5.1% contrast) from a 1T scanner, where all 10 spokes are visible. The right image is also slice 7, but from a 0.3T scanner, where 7 spokes are visible. One or two objects in the eighth spoke are seen, but the outermost object is no more apparent than background noise, so the eighth spoke is not counted, nor are any spokes beyond the eighth spoke.

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.

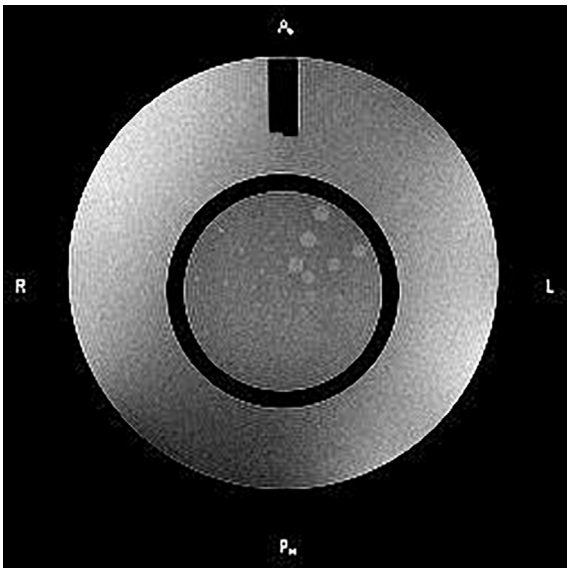


Figure 8. Slice 11 of a 1.5T scanner where the phantom is tilted from head to foot. The upper portion of the LCD plate is within the selected slice, but the lower portion of the plate is tilted out of the acquired slice plane, resulting in only 3 spokes being fully detected before scoring is stopped. Note that spokes 8 and 9 are fully detected but are not counted in the spoke score because not all 3 objects in spoke 4 (and in spokes 5–7) are detected.

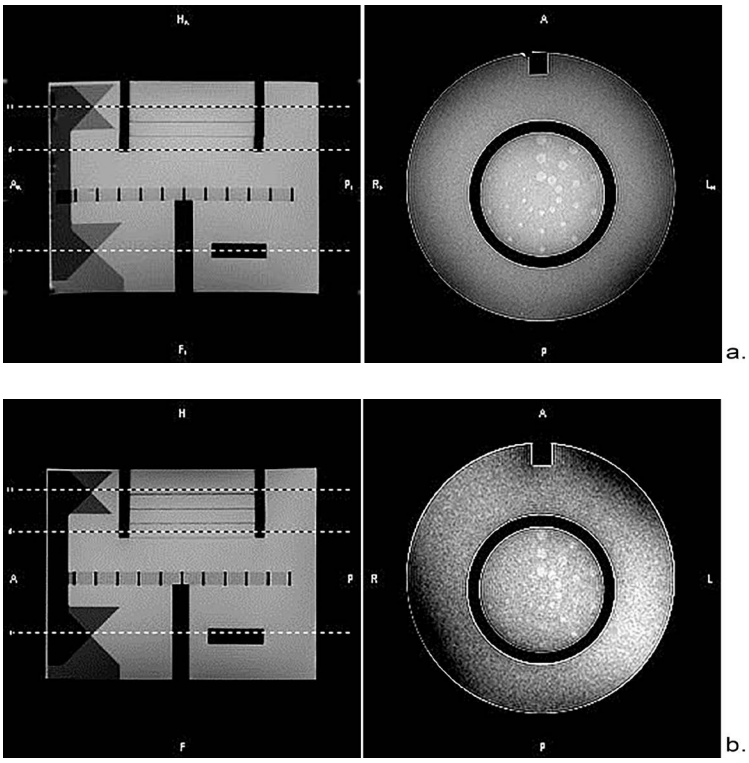


Figure 9. Sagittal localizer showing slice positioning (left) and slice 8 (right) from two different 1.5T MRI systems. a) Proper slice positioning, shown by the overlaps of slices 1 and 11 on the intersection of the crossed wedges, slice 11 on the highest contrast (5.1%) LCD plate, and slice 8 on the lowest contrast (1.4%) plate. All 10 spokes are visible in slice 8. b) Misalignment of slices on the ACR phantom, resulting in only six spokes being detected in slice 8.

DATA INTERPRETATION AND 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).

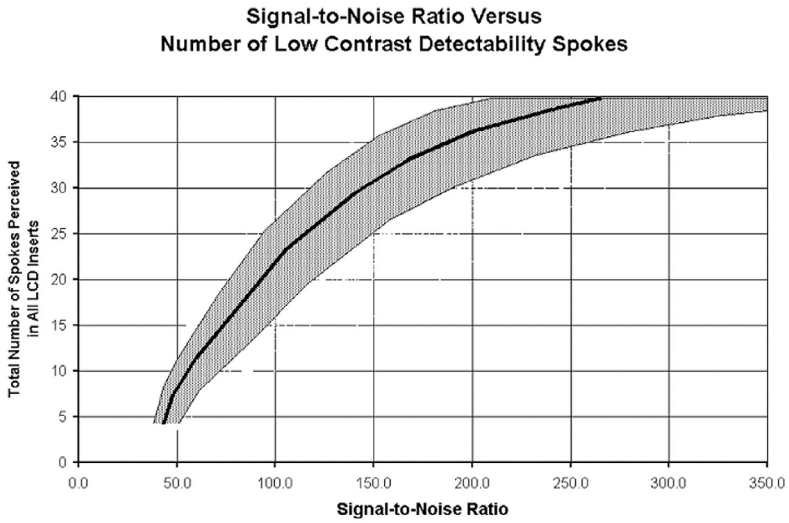


Figure 10. Relationship between the total number of low-contrast spokes (in slices 8–11 combined) perceived on the ACR large phantom and the signal-to-noise ratio. The shaded area represents +1 standard deviation in total spoke score. The number of spokes visualized can also be degraded by poor positioning or image artifacts.

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.

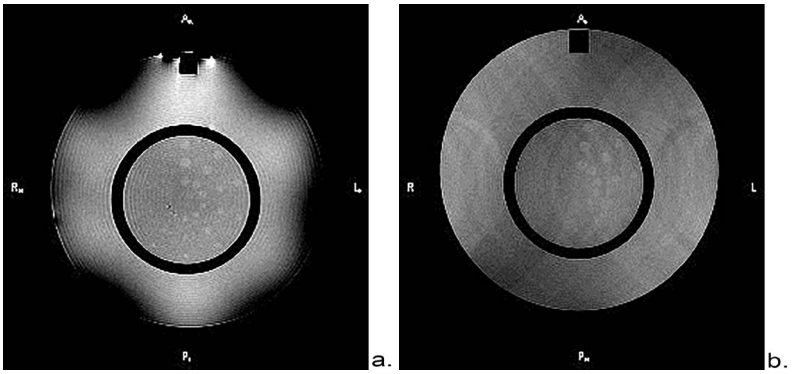


Figure 11. Slice 8 from two different MRI systems. a) Truncation artifacts visible as repeating light-dark bands near sharp interfaces in the ACR phantom tend to obscure low-contrast objects. Air bubbles appearing as black-white dots can also obscure test objects, as those at the innermost objects in spokes 7 and 8. b) Ghost artifacts also obscure test objects. When this occurs, the source of ghosting should be determined and eliminated by a qualified service engineer.

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

OBJECTIVE

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 QUALITY 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. Densitometer
2. Film printer QC chart

About the SMPTE Test Pattern

The 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.

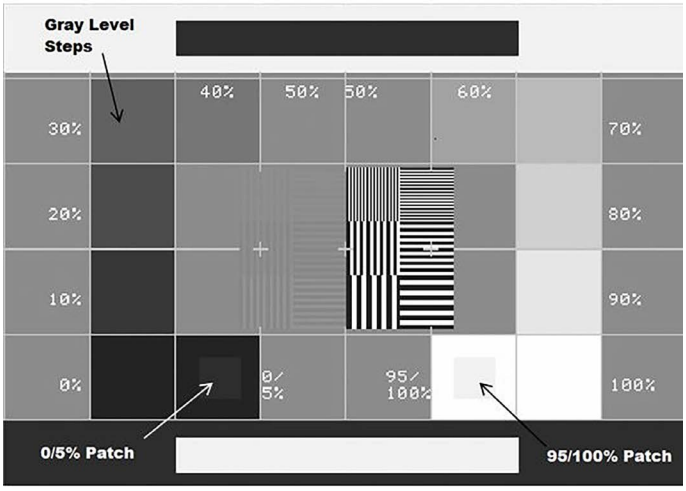


Figure 12. The central portion of the SMPTE test pattern with gray level steps, 0/5% patch and 95/100% patch.

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 FILM 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 AND 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 Limits
0	2.45	±0.15
10%	2.10	±0.15
40%	1.15	±0.15
90%	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 AND 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.

SUGGESTED PERFORMANCE CRITERIA AND 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.

REFERENCES

1. ACR Practice Parameter for Performing and Interpreting Magnetic Resonance Imaging (MRI)
2. ACR-AAPM Technical Standard for Diagnostic Medical Physics Performance Monitoring of Magnetic Resonance Imaging (MRI) Equipment
3. Samei E, Badano A, Chakraborty D, et al. *Assessment of display performance for medical imaging systems, report of the American Association of Physicists in Medicine (AAPM) Task Group 18*. Madison, WI: Medical Physics Publishing; 2005.
4. Kagadis GC, Walz-Flannigan A, Krupinski EA, et al. Medical imaging displays and their use in image interpretation. *RadioGraphics*. 2013;33: 275–290.

APPENDIX

Keeping orderly records of the QC tests is as important as doing them. If there is no record or there is an unintelligible record of the QC test results, then they might as well not have been done. The following datasheets are formatted so that important information can appear in a compact, readable space. The data forms cover the following three areas of the MRI equipment quality control process:

- Weekly Technologists' Quality Control
- Weekly System Visual Checklist
- Weekly Film Printer Quality Control

These data sheets should be stored in a safe place near the scanners for easy review. Copies of the qualified medical physicist's or MRI scientist's quarterly or annual QC report should be stored in the same location to facilitate data review and comparison.

All completed data forms should be reviewed and signed by the qualified medical physicist or MRI scientist at the quarterly or annual equipment review. At that time suggestions for improvement of the MRI equipment quality control process should be considered.

A. Weekly Technologist's Quality Control

Access the Small Phantom Weekly MR Equipment QC Form.

Access the Large Phantom Weekly MR Equipment QC Form.

B. Weekly System Visual Checklist

Access the Weekly System Visual Checklist.

C. Weekly Film Printer Quality Control

Access the Film Printer QC Form.

ACR®
AMERICAN COLLEGE OF RADIOLOGY

QUALITY IS OUR IMAGE

2015
Magnetic Resonance Imaging

QUALITY CONTROL MANUAL

Medical Physicist's/MRI Scientist's Section

REVISIONS

Date	Page(s)	Section	Description of Revisions

ROLE OF THE QUALIFIED MEDICAL PHYSICIST OR MRI SCIENTIST IN THE IMAGE QC PROGRAM

The success of magnetic resonance imaging (MRI) depends on the production of high-quality images. These images must faithfully represent the anatomy, pathology and physiologic function of patients imaged. Production of such images is a difficult task.

Although equipment service engineers and technologists are often involved in MRI calibration and testing, they typically report how well instrument values conform to some set of specifications, which are assumed to determine whether the MRI system is performing in an adequate manner. The qualified medical physicist/MRI scientist is uniquely qualified to perform tests and analyze data to determine which sets of specifications are relevant to a particular imaging problem. Often these tests allow the medical physicist/MRI scientist to recognize equipment failures before they unacceptably degrade the clinical magnetic resonance images. The medical physicist/MRI scientist can also perform tests to determine if imaging irregularities can be attributed to procedural or equipment errors. The tests performed by the medical physicist/MRI scientist are also useful to help understand the design strategy used in producing a particular MRI scanner and recommend the equipment specifications most appropriate for a given practice.

It is the responsibility of the qualified medical physicist/MRI scientist conducting these tests to accurately convey test results in a written report, to make recommendations for corrective actions according to the test results, and to review the results with the radiologists and technologists working with each scanner. In the written performance report, the medical physicist/MR scientist should specifically include the comparison of current test results with the baseline values and report trends when appropriate. This is particularly important in reporting coil performance.

Corrective action should not be limited to repair of MRI equipment by a qualified service engineer, and should also include recommendations concerning use of radiofrequency (RF) coils, appropriateness of pulse sequences, image processing, viewing conditions and the quality control (QC) process. The qualified medical physicist/MRI scientist must periodically (at least annually) review the results of the routine QC tests conducted by the technologist and make appropriate recommendations regarding these tests. Furthermore, the qualified medical physicist/MRI scientist must participate in periodic reviews of the MRI QC program as a whole to ensure that the program is meeting its objectives. The periodic review should specifically include an evaluation of the site's safety guidelines, practices, and policies.

> **Note:** If there is need for corrective action, the medical physicist should instruct the facility to provide a copy of the medical physicist's annual system performance evaluation to the equipment service engineer.

The ACR-AAPM Technical Standard for Diagnostic Medical Physics Performance Monitoring of Magnetic Resonance Imaging (MRI) Equipment [1] sets a basic level of tests that should be performed. This ACR Magnetic Resonance Quality Control Manual expands on those tests, providing guidance on the conduct, analysis and interpretation of results.

Both large and small ACR MRI accreditation phantoms may be used for performing these measurements. In this manual, it is assumed that the QC technologist typically performs these tests after a qualified medical physicist/MRI scientist has determined the range and sensitivity of these tests for a particular MRI scanner and has set up action limits. These recommendations have been incorporated into the weekly QC routines, which are specified in the MRI Technologist's Section of this manual.

A. Changes Since 2004 Version

It should be noted that the list of tests and the following test descriptions are somewhat different from the tests and descriptions of the *2004 ACR Magnetic Resonance Imaging Quality Control Manual*. Specifically, the tests for interslice RF interference have been removed from the list and significant revisions to the recommended procedures for magnetic homogeneity and percent image uniformity (PIU) assessments have been made. The RF cross-talk assessment was removed in light of the fact that essentially all modern systems were found to be capable of easily meeting the guideline of maintaining at least 80% SNR when comparing 0-gap images to 100% slice-gap images. However, it is emphasized that it is the responsibility of the qualified medical physicist/MRI scientist to determine if this assumption is appropriate for each specific system being evaluated and to add a cross-talk assessment when indicated. Alternative approaches to the magnetic field homogeneity assessment were identified to assist the qualified medical physicist/MRI scientist when evaluating systems that do not allow access to phase-angle images. In addition, previously implemented changes in image uniformity, PIU >87.5% for systems up to and including 1.5T and PIU >82% for 3T systems have now been incorporated. We also have added criteria for signal ghosting (<2.5%) and low-contrast detection (a total of at least nine rows of test objects for 1.5T and below, and at least 37 rows of test objects for 3T systems) to the manual to be consistent with the ACR MRI Accreditation Program requirements. Other revisions have been made to improve clarity.

The annual performance evaluation must also include an assessment of the MRI safety program (Section IV.F) in addition to an inspection of the mechanical integrity of the system. The annual performance evaluation will comprise a protocol that the medical physicist/MRI scientist can use to assess the functionality of an MRI scanner and to measure its reliability by repeating these tests at regular intervals over time. Part III of this section describes how the qualified medical physicist/MRI scientist can set up tests for weekly QC and establish action limits. Part IV describes tests that comprise an annual equipment evaluation by the qualified medical physicist/MRI scientist. Part V is a list of references, and Part VI

is an appendix, which contains an MRI Equipment Evaluation Summary form and MR Safety checklist as well as a description of Hard Copy (Film) Quality Control Operating Levels. The qualified medical physicist/MRI scientist may use a data report format of his or her choice as long as the required information is present.

The ACR has taken guidance from the test procedures outlined in the National Electrical Manufacturers Association (NEMA) publications on standards for MRI image quality and from the American Association of Physicists in Medicine (AAPM) Report of MR Subcommittee Task Group I. The documents most relevant to the writing of this manual include the following:

- MS 1-2008: Determination of Signal-to-Noise Ratio in Diagnostic Magnetic Resonance Images
- MS 2-2008: Determination of Two-Dimensional Geometric Distortion in Diagnostic Magnetic Resonance Images
- MS 3-2008: Determination of Image Uniformity in Diagnostic Magnetic Resonance Images
- MS 5-2010: Determination of Slice Thickness in Diagnostic Magnetic Resonance Imaging
- MS 6-2008: Determination of Signal-to-Noise Ratio and Image Uniformity for Single-Channel, Non-Volume Coils in Diagnostic Magnetic Resonance Imaging (MRI)
- MS 9-2008: Characterization of Phase Array Coils for Diagnostic Magnetic Resonance Images

  These documents and other MR-related NEMA standards can be obtained from the NEMA website (www.nema.org) [2,3,4,5,6,7].
- AAPM Report No. 100: Acceptance Testing and Quality Assurance Procedures for Magnetic Resonance Imaging Facilities

This document and other MR-related reports can be obtained from the AAPM website (www.aapm.org) [8].

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 $NiCl_2$ 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 $NiCl_2$ 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

More detailed information on the ACR MRI accreditation phantom can be found in the ACR documents and is downloadable from www.acr.org [9,10,11,12]:

- Site Scanning Instructions for Use of the MR Phantom for the ACR MRI Accreditation Program
- Site Scanning Instructions for the Use of the Small MR Phantom for the ACR MRI Accreditation Program
- Phantom Test Guidance for the ACR MRI Accreditation Program
- Phantom Test Guidance for Use of the Small MRI Phantom for the ACR MRI Accreditation Program

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 (B_0) 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 (f_0) that matches the B_0 (in Tesla) according to the Larmor equation:

$$f_0 = \left(\frac{\gamma}{2\pi}\right) B_0$$

Where γ is the gyromagnetic ratio for the nucleus under study. For hydrogen nuclei, the quantity $\left(\frac{\gamma}{2\pi}\right)$ 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 B_0 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).

$$\%GD = \frac{true\ dimension - observed\ dimension}{true\ dimension} \times 100$$

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 (B_0) 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.

B_0 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 B_0 homogeneity, it is possible that abnormally high B_0 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, B_0 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.

Table 1. Recommended slice of the ACR large MRI phantom to use for weekly low-contrast detection QC and typical number of spokes visible in the recommended slice and on all slices as a function of magnetic field strength.

Low-Contrast Detectability Recommendations by Field Strength for Large ACR Phantom for the ACR T1 Series			
Field Strength	Recommended weekly QC slice #	Typical number of spokes visible in recommended QC slice	Total number of spokes on all slices
0.2	11	4	12
0.3	11	5–7	21
0.5	10	6–9	27
0.7	10	6–8	31
1.0	9	7–8	34
1.5	8	6–9	36
2.0	8	9–10	38
3.0	8	10	40

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 [19] and Haacke et al [20].

ANNUAL MRI SYSTEM PERFORMANCE EVALUATION

The annual MRI system performance evaluation must include the previously described technologist QC measurements, scanning and analyzing the ACR MRI phantom as submitted for accreditation, and the measurements described below and listed in Table 2. The method for performing these measurements may vary according to the needs of the facility and the preference of the medical physicist/MRI scientist. If the medical physicist/MR scientist is using other than ACR-specified methods, the alternative methods should be fully documented for the facility's record. For some of these tests, the ACR MRI accreditation phantom may not be the most appropriate tool. In addition, many of these values will be system-specific, and baseline values will have to be determined when the system is commissioned or when the qualified medical physicist/MRI scientist first undertakes a performance analysis. In the written performance report, the medical physicist/MRI scientist should specifically include the comparison of current test results with the baseline values and report trends when appropriate. At the time of these tests, the qualified medical physicist/MRI scientist also reviews the weekly QC records, service logs, and safety policies and procedures, and recommends changes in QC program procedures indicated by these data.

Table 2. Specific Required Tests Required for Annual MRI System Performance Evaluation

	Performance Tests (Those in italics indicate tests that can be performed by scanning the ACR MRI Phantom)	Technologist QC (Weekly)	Medical Physicist/ MR Scientist (Annually)
1	Setup and Table Position Accuracy	X	X
2	Center Frequency	X	X
3	Transmitter Gain or Attenuation	X	X
4	*Geometric Accuracy Measurements*	X	X
5	*High-Contrast Spatial Resolution*	X	X
6	*Low-Contrast Detectability*	X	X
7	Artifact Evaluation	X	X
8	Film Printer Quality Control (if applicable)	X	X
9	Visual Checklist	X	X
10	Magnetic Field Homogeneity		X
11	*Slice-Position Accuracy*		X
12	*Slice-Thickness Accuracy*		X
13	Radiofrequency Coil Checks		X
	a. SNR		X
	b. Percent Image Uniformity (PIU)		X
	c. Percent Signal Ghosting (PSG)		X
14	Soft-Copy (Monitor) Quality Control		X
15	MR Safety Program Assessment		X

A. Magnetic Field Homogeneity

OBJECTIVE

Homogeneity refers to the uniformity of the main magnetic field strength B_0 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 B_0 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 $\pi/2$ 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 AND ANALYSIS

1. Measure the FWHM of the spectral peak. Convert the FWHM from Hz to ppm of the B_0 field strength (in Tesla) using the Larmor equation:

$$FWHM(ppm) = \frac{FWHM(Hz)}{42.576 B_0\,(T)}$$

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 (FOV_x) the frequency-encoding gradient strength (G_x) is a function of receiver bandwidth (BW_x), it is possible to estimate field homogeneity (ΔB_0) by comparing the spatial distortion (d_1 - d_2) observed at the same FOV_x for both small (BW_1) and large (BW_2) bandwidth acquisitions (Figure 1).

The following equation is used for estimating the magnetic field inhomogeneity in ppm, using the bandwidth-difference option:

$$\Delta B_0\,(ppm) = \frac{(BW_1 \times BW_2)\; x\; (d_1 - d_2)}{42.576 MHz/T \times B_0(T)\; x\; FOV_x \times (BW_2 - BW_1)}$$, where

BW_1 = smallest available receiver bandwidth (Hz)

BW_2 = largest available receiver bandwidth (Hz)

(d_1 - d_2) = spatial distortion (mm) measured as the distance difference of corresponding points in the phantom in the frequency-encoding direction for a specified DSV

FOV_x = 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:

$$\boldsymbol{BW\ (Hz) = 125\frac{Hz}{pixel} \times 256\ pixels = 32{,}000\ Hz}$$

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:

$$\boldsymbol{at\ 1.5T:\ FD(Hz) = 3.5\ ppm \times 63\frac{Hz}{pixel} = 220\ Hz}$$

$$\boldsymbol{at\ 3.0T:\ FD(Hz) = 3.5\ ppm \times 127\frac{Hz}{pixel} = 440\ Hz}$$

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:

$$\boldsymbol{BW(Hz) = \frac{220Hz \times 256\ pixels}{1.75\ pixels} = 32{,}183Hz}$$

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 BW_1, 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 BW_2, 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 BW_1 and BW_2 images in each orthogonal plane before repositioning the phantom to assess all three planes.

DATA INTERPRETATION AND 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 BW_1. 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 "d_1."

4. Repeat Steps 1–3 for the same reference points and corresponding slice position acquired with bandwidth BW_2. Record the measured length (mm) as "d_2." 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 (d_1 - d_2) 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 ΔB_0 using the equation above for each orientation. This value is the inhomogeneity (in ppm) for the specified diameter.

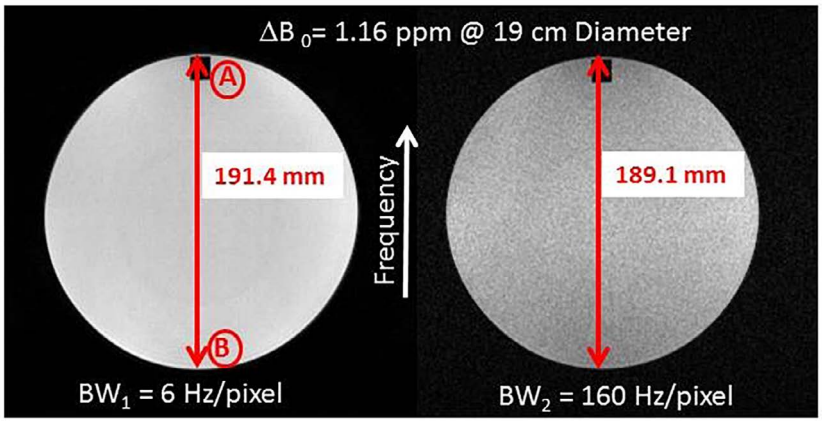


Figure 1. Images illustrate the bandwidth-difference option; (left) axial magnitude image acquired with the system's smallest receiver bandwidth value (BW^1= 6 Hz/pixel); (right) image acquired with system's largest receiver bandwidth value (BW^2= 160 Hz/pixel). The frequency-encoding direction is vertical in the image.. The frequency matrix was 256 pixels, 25-cm FOV and B_0 field strength of 0.3T, resulting in a magnetic field inhomogeneity of 1.16 ppm.

3. Phase Map Option

TEST PROCEDURE

This test provides an accurate upper bound measurement of B_0 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 INTERPRETATION AND ANALYSIS

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 labeled 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.

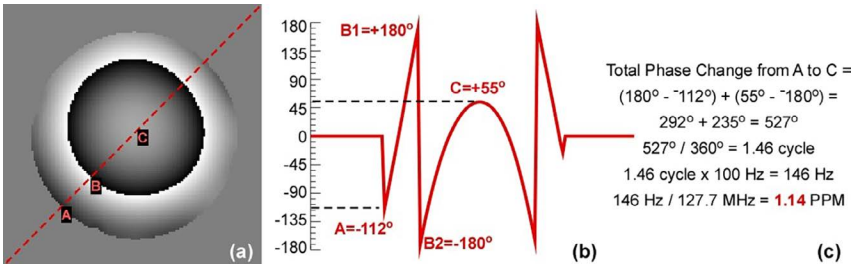


Figure 2. Image data for axial phase map option obtained on a 3T scanner. CF = 127.7 MHz, TE 10 ms. a) Phase image. b) Phase profile along diagonal through the image. c) Calculation of total phase change from point A to point C of 1.14 ppm.

The graph in Figure 2b depicts a profile of the phase values along the diagonal line of Figure 2a. For clarity, values have been scaled to represent the phase in degrees. This diagonal was chosen because from visual inspection it appeared to encompass the largest changes in phase across the image. The total phase change from point A to point C is calculated as the sum of the phase change from A to B plus the change from B to C, where the phase at point B can be ±180 as appropriate. In this case the total phase change was 527°. Dividing this by 360° yields a total phase change of 1.46 cycles. Since a TE of 10 ms was used, one cycle corresponds to 100 Hz; therefore, the total frequency change is 146 Hz. Finally, dividing this by the center frequency of 127.7 MHz (for this 3T scanner) yields a peak-to-peak magnetic field inhomogeneity of 1.14 ppm.

The calculation above represents the inhomogeneity of the magnet in that one axial slice. To properly evaluate magnet inhomogeneity, phase maps in multiple slices in axial, sagittal, and coronal planes need to be evaluated. Figure 3 shows a similar dataset and calculations in the coronal plane, where the inhomogeneity is determined to be 0.98 ppm. An even smaller inhomogeneity was found in the sagittal plane (not shown). Comparing the results from all three planes, we report that the magnet inhomogeneity does not exceed 1.14 ppm. In fact, the homogeneity of this magnet is better than that, as shown below by the phase-difference method on the same scanner.

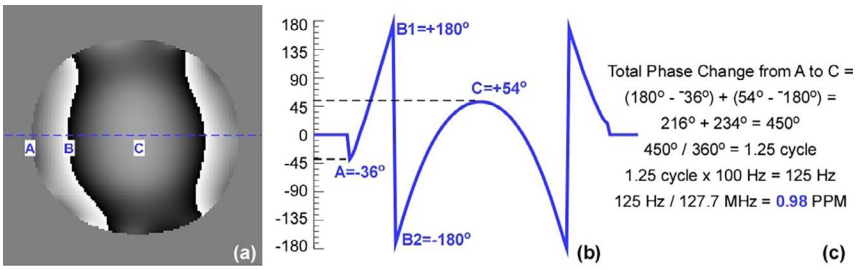


Figure 3. Image data for coronal phase map option obtained on a 3T scanner. Center frequency = 127.7 MHz, TE 10 ms. a) Phase image. b) Phase profile along horizontal line through the image. c) Calculation of total phase change from point A to point C.

4. Phase-Difference Map Option

TEST PROCEDURE

The test procedure for the phase-difference map option is identical to the phase map option discussed above with the addition of a second set of phase images obtained using a slightly longer TE, from 2.5 to 10 ms longer. Greater TE differences yield greater sensitivity, but with the need to deal with a larger number of phase wraps.

DATA INTERPRETATION AND ANALYSIS

Figure 4a is the phase map at TE=15 ms. Figure 4b is the corresponding phase map with TE=10 ms, the same phase map shown in Figure 2a. Figure 4d depicts the phase profiles through both images. Note that the total phase change of the TE=15 ms image corresponds to 0.89 ppm, whereas the phase change of the TE=10 ms image is 1.14 ppm. Remember that the total phase change is the net result of magnet inhomogeneity and contributions from "other" sources, such as off-centering of the sample window (fractional echo), nonuniform RF penetration, and magnetic susceptibility differences. Although these other sources do not change with TE, the portion of the phase change caused by magnet inhomogeneity increases with increasing TE. The phase-difference method is more accurate than the single phase map method because it removes the effects of these other sources of inhomogeneity.

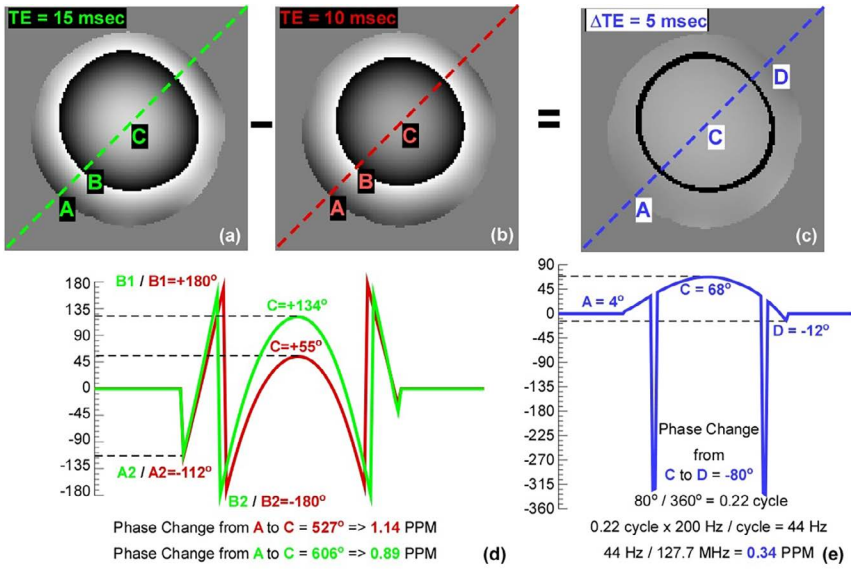


Figure 4. Image data for axial phase-difference option obtained on the same 3T scanner as Figure 2. Center frequency = 127.7 MHz. a) Phase image for TE = 15 ms. b) Phase image for TE = 10 ms. c) Phase-difference image. d) Phase profile along diagonal through the images: image 4a (green) and image 4b (red). e) Phase profile along the diagonal (blue) of the phase-difference image and the calculation of the total phase change from point C to point D within the phase-difference image.

Figure 4c displays the result of subtracting the TE 10 ms phase image from the TE 15 ms phase image. Note that the dark ring in the phase-difference (subtraction) image (Figure 4c) resulted because the phase wrap did not occur at exactly the same location in the two images. In some cases, these misalignments could complicate the final analysis, but not in this case. Figure 4e shows the diagonal profile through the difference image. The large discontinuities can be completely ignored and, in this case, have no effect on the calculations. From the profile, we see that the net phase change from point C to point A is 64°, whereas the change from C to D is 80°. The net difference in the two echo times is 5 ms, which corresponds to 200 Hz per phase cycle. The phase difference of 80° divided by 360° per cycle is multiplied by 200 Hz, yielding a 44 Hz peak-to-peak variation. Dividing this by 127.7 MHz results in a magnetic field inhomogeneity of 0.34 ppm. This is a much smaller (and more accurate) value than is calculated using either single phase image alone.

As stated in the phase map option above, it is necessary to examine the phase shifts in multiple planes. Figure 5a shows the phase-difference image (TE 15 ms - TE 10 ms) in the coronal plane. Note that the regions of phase wrap misalignment show up as two irregular bands running top-to-bottom in the image (head-to-foot in the scanner [H/F]). These are cross sections of the ring seen in the axial phase-difference images. In the phase map option above, we noted that the largest phase change went from left to right. In this phase-difference image and the corresponding profile (red) in Figure 5d, we see that the largest phase change is in the H/F direction. The calculations in Figure 5e show that the change from A to C corresponds to 0.63 ppm, whereas the change from C to E corresponds to

0.55 ppm. Combining these results with those obtained from the phase-difference image in the axial plane, we would report that the magnetic field inhomogeneity does not exceed 0.63 ppm.

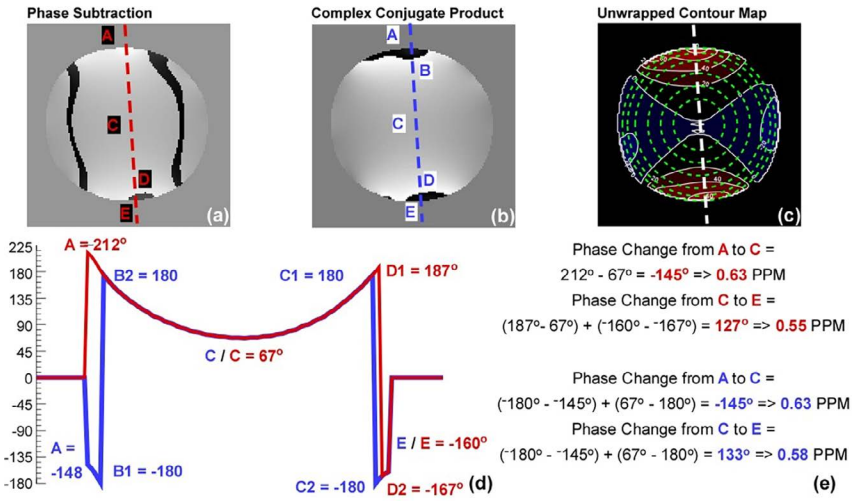


Figure 5. Image data for phase-difference option obtained on a 3T scanner in the coronal plane. a) Difference image obtained by simply subtracting the two coronal phase maps (TE 15 ms - TE 10 ms). b) Difference image obtained by multiplying the complex (real and imaginary) version of the TE 15 image by the complex conjugate of the TE 10 images. c) Contour plots of image 5b after phase unwrapping. d) Profiles through image 5a (red) and image 5b (blue). e) Calculation of the total phase change from location A to location C and from location C to location E.

Note that the phase discontinuity at point D in Figure 5a does not equal 360° but equals 347°. When simply subtracting two phase images, the bands at discontinuities can take on virtually any phase value depending on the rate of change near the discontinuities in each original image. This makes it very important to closely examine the actual values on both sides of the discontinuity. Another method of calculating phase-difference images that is immune to these variations caused by the misalignment of phase wrap is provided below. Although MR images are normally displayed as magnitude images or sometimes phase images, the underlying data are actually complex, with real and imaginary components. The relationship between the magnitude and phase representation and the real and imaginary parts is presented in equations below:

$$S_{(complex)} = Ae^{i\theta} = S_{(real)} + i \times S_{(imaginary)}$$

$$S_{(real)} = A \times cos\ (\theta)$$

$$S_{(imaginary)} = A \times sin\ (\theta)$$

Where the complex pixel signal value S is represented in terms of its magnitude (A) and phase (θ) or as its real and imaginary components; i = the square root of -1. Assume we have two images, X_1 and X_2, with magnitudes and phases of A_1, θ_1 and A_2, θ_2. For the phase-difference method we want the difference $\theta_1 - \theta_2$ of each pixel in the image. This phase difference can be obtained by multiplying the complex version of image 2 by the complex conjugate of image 1 as described below:

$$X_{delta} = X_2 \times conj(X_1) = A_2 \times e^{i\times\theta_2} \times A_1 \times e^{-i\times\theta_1} = A_2 \times A_1 \times e^{i(\theta_2 - \theta_1)}$$

or

$$X_{delta} = X_2 \times conj(X_1) = (R_2 + i \times I_2) * (R_1 - i \times I_1) = R_2 \times R_1 + I_2 \times I_1 + i \times (I_2 \times R_1 - R_2 \times I_1)$$

$$X_{imaginary} = I_2 \times R_1 - R_2 \times I_1$$

$$X_{real} = R_2 \times R_1 + I_2 \times I_1$$

$$\theta_2 - \theta_1 = atan(X_{imaginary}/X_{real})$$

Where "R" stands for real component, and "I" stands for imaginary component. This image processing method is not available on any MRI scanner but can be done if complex image data can be processed on an independent workstation. This complex conjugate method was used to generate the image in Figure 5b. The misalignment bands are eliminated, and what remains are normal 360° phase wraps at the superior and inferior edges of the phantom. As long as offline processing is being done, from this image it is possible to unwrap the image and plot contours of the phase map, as shown in Figure 5c. The red regions represent a positive change in the frequency (and field), and the blue regions represent a negative change.

It was stated earlier in the phase map option section that some vendors perform image processing that can adversely affect the determination of the phase scaling. This problem is avoided when using real and imaginary images since these images have no discontinuities, so their values always change smoothly. By using the real and imaginary images, it is straightforward to calculate true phase images with discontinuities that are exactly 360°.

The final value of 0.63 ppm as the inhomogeneity of the 3T image is substantially different than that of 1.14 ppm found by using the phase map option. A large part of this error can be avoided if an oil-filled phantom is used, since oil does not suffer from the same RF penetration problems as water. Figure 6 below shows phase-difference image calculations using identical scan parameters, but with a 32-cm oil-filled phantom.

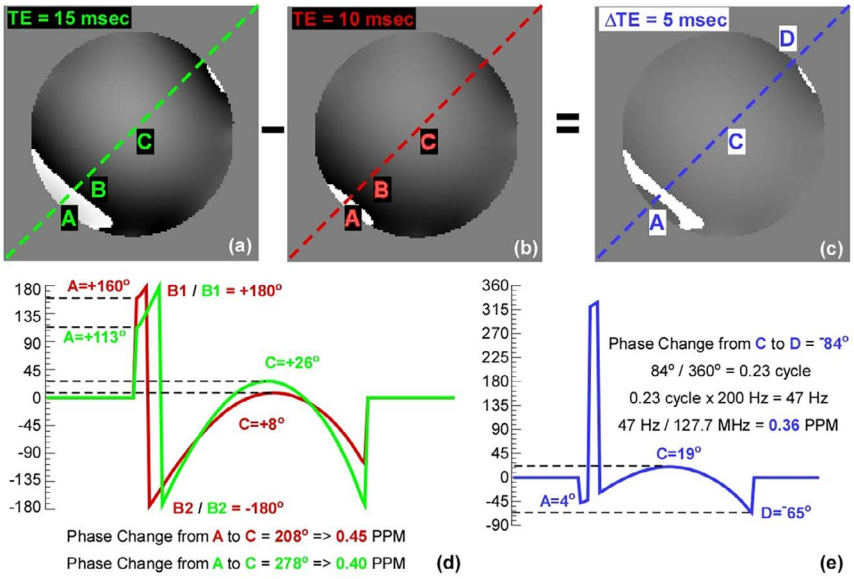


Figure 6. Image data for axial phase-difference option obtained on the same 3T scanner with an oil-filled phantom. a) Phase image TE = 15 ms. b) Phase image TE = 10 ms. c) Phase-difference image. d) Phase profiles along diagonals through the images. e) Phase profile of difference image and calculation of total phase change from point C to point D.

Note that the two individual phase images result in estimates of inhomogeneity of 0.45 ppm and 0.40 ppm as opposed to estimates of 1.14 ppm and 0.89 ppm obtained with the water-filled phantom. By eliminating the phase changes caused by RF penetration differences, accuracy of the phase map option has been significantly improved.

Some MRI vendors actually provide dual-echo imaging sequences that provide a magnitude image and a phase-difference image (or images). This greatly simplifies the analysis process. Figure 7 below shows an example at 0.6T where the dual-echo image used TEs of 11.2 and 19.1 ms. The difference of 7.9 ms represents a frequency of 126.6 Hz; at 0.6T (25.5 MHz) this corresponds to 5 ppm per phase cycle.

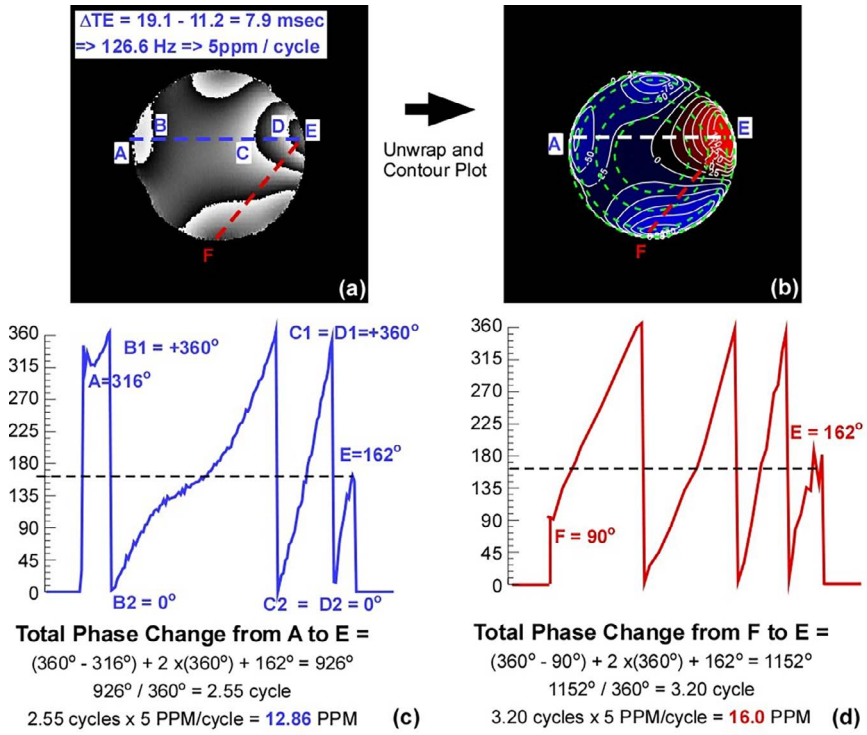


Figure 7. Image data for an axial phase-difference option obtained on a 0.6T upright scanner with a water-filled phantom. a) Phase-difference image provided by scanner software. b) Color contour plots obtained after offline phase unwrapping. c) Phase profile from point A to E; d) Phase profile from point F to E.

In previous examples we looked at profiles that went across the phantom diagonally (Figures 2, 4, 6), horizontally (Figure 3), and vertically (Figure 5). Sometimes the path between the two points with the greatest phase difference is completely different. In Figure 7a the horizontal (blue) path from A to E resulted in an estimate of 12.86 ppm. The shorter path (red) at an angle between points F and E resulted in an estimate of 16.0 ppm. Calculating both of these values required paying close attention to the phase wraps. Although it is possible to estimate the magnet homogeneity by simply counting the number of phase wraps in an image, it is best to actually plot profiles of various chords across the phantom.

FINAL COMMENT ON PHASE MAPS AND PHASE DIFFERENCE

It has been stated above that it is necessary to make homogeneity measurements in all three planes. Obtaining only one image (or pair of images) through the isocenter in each of the three planes, however, is not adequate. Multiple slices in each plane (or 3-D volume data) are required to ensure that small localized problems are not missed. Figure 8 shows a series of phase map images in all three planes. The three images through isocenter are outlined by red boxes. These three images look completely normal. On the left side, indicated by the arrows, is a well-defined region of high magnetic field inhomogeneity. This type of phase map arises when metal is present in the bore of the scanner.

The site from which this 3-D phase map was acquired had reported consistent problems with the fat saturation of right shoulder and left hip images. Service engineers found nothing in the magnet bore and reported

that the magnet met magnetic field homogeneity specifications. Prior to submitting for re-accreditation, the medical physicist/MRI scientist performed an annual performance evaluation, obtained these images, and failed the unit for excessive magnet inhomogeneity. In addressing the physicist report, service engineers removed the cover from the magnet bore and found a bobby pin underneath the covering in a location corresponding to the region of high magnetic field inhomogeneity. This problem would not have been identified and corrected if only the spectral peak method had been used or if phase maps had been obtained in each of three orthogonal planes only through isocenter.

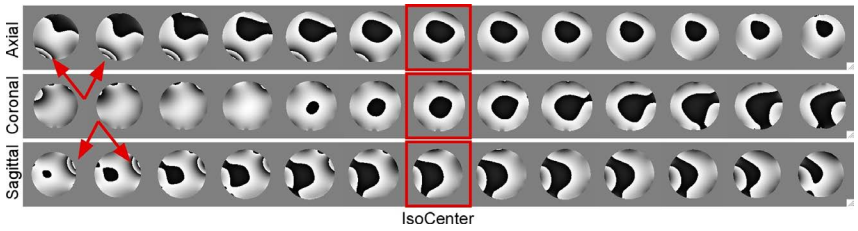


Figure 8. A series of multiplanar reformatted phase images from a 3-D GRE scan. The slices through isocenter (red boxes) appear completely normal. The images on the far left, indicated by the red arrows, show a well-defined region of field inhomogeneity that was caused by a bobby pin under the magnet bore cover.

SUGGESTED PERFORMANCE CRITERIA AND CORRECTIVE ACTION

Magnetic field homogeneity data should be reported in the annual system performance evaluation report. The homogeneity is specified by the MRI system manufacturer. The values obtained should be compared to those specified for the DSV equal to the phantom diameter.

Magnetic field homogeneity requirements become more stringent for systems used for ultrafast imaging, fat suppression, and/or spectroscopy.

Poor magnetic field homogeneity can be due to ferromagnetic objects contaminating the field within the bore (or gap) of the magnet. Changes in the location or arrangement of large ferromagnetic objects in the exterior environment of the magnet can also cause magnetic field inhomogeneities.

Often magnetic field homogeneity problems can be corrected through adjustment of the gradient offsets. If the homogeneity is very poor, the service engineer can measure it using a special jig that measures resonant frequency in a small sample at various locations within the magnet. These measurements can be compared to those made at the time of installation. In some extreme cases, superconducting shim currents will have to be adjusted.

B. Slice-Position Accuracy

OBJECTIVE

The ACR slice-position accuracy test checks the accuracy with which axial slices are positioned at specific locations utilizing a sagittal localizer image. This test determines whether the actual locations of acquired slices differ from their prescribed locations by substantially more than is normal for a well-functioning scanner.

TEST PROCEDURE

Differences between the prescribed and actual positions of slices 1 and 11 for the large phantom and slice 1 for the small phantom for the ACR T1 and T2 series are measured. These measurements are typically made using the ACR T1-weighted axial scanning series (MRI Technologist's Section IV.B and IV.C).

For the large phantom, slices 1 and 11 are originally positioned so that they are aligned with the vertices of the crossed 45° wedges at the inferior and superior ends of the phantom, respectively. The two crossed wedges in slices 1 and 11 appear as parallel dark, vertical bars at the top (anterior side) of the phantom. For both slice 1 and slice 11 the wedges will appear as dark bars of equal length on the image if the slice is exactly aligned with the vertex of the crossed wedges. If the slice is located superior to the vertex, the right bar on the image (anatomical left) will be longer. If the slice is displaced inferior to the vertex, the left bar will be longer.

For the small phantom, slice 1 in each ACR series is prescribed to align with the center of the crossed 45˚ at the starting end of the phantom. The crossed wedges appear as a pair of adjacent, dark, vertical bars at the top (anterior side) of the phantom. If slice 1 is exactly aligned with the center of the crossed wedges, then the wedges will appear as dark bars of equal length on the image. If the slice is displayed superiorly with respect to the center, the bar on the observer's right (anatomical left) will be longer. If the slice is displayed inferiorly with respect to the center, the bar on the left will be longer.

Measurements are made for slices 1 and 11 of the ACR T1-weighted axial series for the large phantom and for slice 1 of the ACR T1 and T2 series for the small phantom.

Use the following procedure for each image:

1. Display the slice magnified on the monitor by a factor of two to four. Keep the vertical bars of the crossed wedges within the displayed portion of the magnified image.
2. Adjust the display window so that the ends of the vertical bars are not fuzzy using a narrow window width. The display level should 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 difference in length between the left and right bars. If the left bar is longer, then assign a minus sign to the length. For example, if the bar-length difference is 5.0 mm and the left bar is longer, then record the measurement as -5.0 mm.

4. Record the measured data in the annual system performance evaluation report.

DATA INTERPRETATION AND ANALYSIS

The action criteria are specified in terms of limits on the bar-length difference measurements, based on a series of baseline data compiled by the qualified medical physicist/MRI scientist.

Since the crossed wedges have 45° slopes, the bar-length difference is twice the actual slice displacement error. For example, a bar-length difference of 5.0 mm implies the slice is displaced inferiorly by 2.5 mm from the vertex of the crossed wedges.

SUGGESTED PERFORMANCE CRITERIA AND CORRECTIVE ACTION

The magnitude of each bar-length difference should be less than or equal to 5 mm. Note that a bar-length difference of more than 4 mm for slice 11 for the large phantom will adversely affect the low-contrast object detectability measurement. A bar-length difference of more than 4 mm for slice 1 for the small phantom may adversely affect the slice-thickness measurements and the low-contrast object detectability.

The most common cause of failure likely is an error by the scanner operator in the prescription of the slice locations. This type of error is ruled out by examining the axial images, which are cross-referenced on the localizer; slices 1 and 11 should be aligned with the crossed wedge vertices on the localizer image. Slices should be prescribed as carefully as possible because these errors in combination with other sources of error can push an acceptable level of performance to an unacceptable level.

Many scanners automatically move the patient table position in the inferior-superior direction to place the center of a prescribed imaging volume at gradient isocenter. After the localizer is obtained, the table position is adjusted so that an error in the table positioning mechanism can lead to a slice-positioning error. If the bar-length difference for slice 1 and slice 11 is the same in sign and similar in magnitude, this type of table positioning error may be the cause.

Sometimes an unfortunate combination of two or three of the problems (inaccurate slice prescription, error in the table-positioning mechanism and poor gradient calibration or B_0 homogeneity) can lead to a failure when no single problem would be sufficiently bad to cause a failure on its own. Therefore, if no one thing seems to be responsible for causing a failure of this test, try having the service engineer shim B_0, recalibrate the gradients, and check the table positioning mechanism for excessive play. Then acquire a new image dataset after prescribing the slices as carefully as possible.

C. Slice-Thickness Accuracy

OBJECTIVE

The slice-thickness test is used to determine the accuracy of a specified slice thickness. The prescribed slice thickness is compared with the measured slice thickness. Poor slice-thickness accuracy may not only suggest that the slices are too thick or thin, but also can adversely affect image contrast and SNR.

TEST PROCEDURE

For this test, the lengths of two signal ramps in slice 1 of the ACR MRI

accreditation phantom are measured for 5-mm thick slices for each of the ACR imaging series.

The slice-thickness measurement performed with the ACR MRI phantoms is similar to one of the methods described by NEMA (NEMA MS-5, 2009). Two thin, oppositely inclined ramps appear in a structure called the slice-thickness insert. If the center of slice 1 is properly positioned at the vertex of the crossed wedges, as shown in Figure 3 of the MRI Technologist's Section, and the phantom is not tilted, the two bright thick lines representing the ramps will appear one above the other. The two ramps are crossed: one has a negative slope and the other a positive slope with respect to the plane of slice 1. The ramps are produced by cutting 1-mm wide slots in a block of plastic. The slots are open to the interior of the phantom and are filled with the same solution that fills the bulk of the phantom. The signal ramps have a slope of 10 to 1 with respect to the plane of slice 1; i.e., they make an angle of about 5.71° with slice 1. Therefore, the signal ramps will appear in the image of slice 1 with a length that is 10 times the thickness of the slice (as shown in Figure 6b of the MRI Technologist's Section for the small phantom). If the phantom is tilted in the right-left direction, one ramp will appear longer than the other. Error introduced by right-left tilt is corrected by averaging the measurements from the two crossed ramps using the slice-thickness formula provided in the next section.

DATA INTERPRETATION AND ANALYSIS

For each ACR imaging series, length of the signal ramps in slice 1 is measured according to the following procedure:

1. Display slice 1 magnified by a factor of two to four while keeping the slice-thickness insert fully visible on the screen.
2. Adjust the display level so that the signal ramps are well visualized. The ramp signal is much lower than that of the surrounding water, so usually it will be necessary to lower the display level substantially and narrow the window width.
3. Place a rectangular ROI at the middle of each ramp. Note the mean signal values for each of the two ROI's, then average the values. This result is a number approximating the mean signal at the middle of the ramps. Record this number as the RAMP SIGNAL LEVEL. An elliptical ROI may be used if a rectangular one is unavailable.
4. Be careful that the ROI's cover the full widths of the ramps in the top-bottom direction, but do not allow any portion of the ROI's to be located outside of the ramps. If there is a more than 20% difference between the signal values obtained for the two ROI's it is often due to one or both of the ROI's including regions outside the ramps.
5. Lower the display level to one-half of the of the average ramp signal calculated in step 3. Set the display window width to its minimum.

6. Use the on-screen length measurement tool of the display station to measure the lengths of the top and bottom ramps. Record these lengths. They are the only measurements required for this test. Record the values measured in the annual system performance evaluation report.

Often the ramps seem to be composed of stripes and the ends appear scalloped or ragged. This striping pattern is due to truncation artifact and is normal. One must estimate the average locations of the ends of the ramps to measure the ramp lengths. A degree of inaccuracy arises from estimating the ends of the ramps but a millimeter of error in the ramp length measurement corresponds to only a tenth of a millimeter error in the slice thickness and this turns out to be a small effect.

SUGGESTED PERFORMANCE CRITERIA AND CORRECTIVE ACTION

The slice thickness is calculated using the following formula:

$$Slice\ Thickness = 0.2 \times \frac{top \times bottom}{top + bottom}$$

where "top" and "bottom" are the measured lengths of the top and bottom signal ramps. For example, if the top signal ramp were 59.5 mm long and the bottom ramp were 47.2 mm long, then the calculated slice thickness would be

$$Slice\ thickness = 0.2 \times (59.5 \times 47.2) / (59.5 + 47.2) = 5.26\ mm$$

Record the value calculated in the annual system performance evaluation report. For the prescribed slice thickness of 5 mm, the ACR performance criterion is that the measured slice thickness should be 5.0 mm ± 0.7 mm.

RF amplifier nonlinearity can cause distorted RF pulse shapes and failure of this test. On many scanners, the service engineer must empirically calibrate the RF power amplifier for linearity.

Malfunctions anywhere in the high-power RF portion of the scanner (RF power amplifier, coaxial cables, RF switch, or in the transmitter coil itself) can produce distorted RF pulse shapes. Poor gradient calibration or poor gradient switching performance also can cause failure of this test.

All of these possible causes for failure require corrective action by the service engineer.

D. Radiofrequency Coil Checks

OBJECTIVE

The design of RF MRI coils always represents a trade-off between maximizing image uniformity and enhancing SNR. Coils that have been designed to image body parts placed within their volumes (head coils, body coils, and some neck and knee coils) will produce very uniform excitation and reception of the MR signal.

Many procedures are now typically performed using surface coils that improve SNR by combining, to various degrees, the following three strategies: (1) placing the coil close to the volume of interest, (2) excluding signal and noise from regions not under investigation and (3) maximizing

the sensitive region of the coil over the volume of interest. Typically, these probes yield very non-uniform images. If the radiologist is aware of these coils' characteristics, however, this perception can be accommodated at interpretation. RF coils, called phased-array coils, have been employed to improve image uniformity from closely coupled RF coils.

At the present time, the following procedures for measuring SNR do not apply to parallel imaging (pMRI) with acceleration factors. Until standard methods for measuring SNR become available, it is recommended that all images be acquired without pMRI acceleration.

The qualified medical physicist/MR scientist may use the QA procedures and tools supplied by the vendor to test the coils.

GENERAL THEORY

Signal-to-Noise Ratio

SNR is a fundamental but very general parameter associated with MRI system performance. The measurement of signal and noise in Fourier MR imaging is a complex subject. Henkelman [22] described how signal intensity measurements are determined in the setting of low SNRs for magnitude reconstructed MR images obtained using linear RF coils. Gudbjartsson and Patz [23] developed a theoretical analysis of the noise statistical properties (Rayleigh distribution) in magnitude and phase Fourier MR images. Constantinides et al [24] provided similar noise distribution functions and correction factors for determining SNR for phased-array RF coils.

The single-acquisition method used in this manual was proposed by Kaufman et al [25]. However, care must be taken to ensure that the ROI in which the "noise standard deviation" is measured is free of artifacts. In addition, measurements in regions of nonuniformities due to bandwidth-limiting filtering, truncation of the background signal data, and RF filtering of the signal data at the edges of the frequency-encoding range should be avoided.

An alternative method of SNR measurement, used by some MRI system manufacturers (NEMA MS1-2008, Method 1), acquires two consecutive scans with identical scan parameters. Sijbers et al [26] have compared the single image acquisition method recommended in this manual with NEMA Method 1 and determined that NEMA Method 1 yields acceptable SNR measurements except in the presence of erratic ghosting or fluid motion. Data directly correlating the two methods, obtained by Firbank et al [27], suggest that the single acquisition method is appropriate in a QA program "since it is quicker and easier to perform and is a good indicator of the more exact procedure."

Whichever method is used to measure SNR, the single most important concept is reproducibility. Tests must be performed the same way each time, and analysis must be done the same way each time. To detect small changes in SNR due to actual equipment failure one needs to ensure that variations due to methodology are kept to a minimum. Because the noise term is both small and in the denominator of the SNR, test design choices that improve the accuracy of the noise measurement are more important

than those that improve the mean signal measurement.

Note that the SNR data recorded in the annual system performance evaluation report using the methods described below are estimates and not rigorous measurements of the true SNR. However, for most systems, this is a reproducible index that is quite adequate for routine QC. For some low-field systems where the background intensity may be significant relative to the signal, it may be necessary to correct the signal by subtracting the background from the signal before calculating the SNR.

Transmitter Gain Measurements

Transmitter gain (or attenuation) is automatically determined by the MRI system during the prescan calibration routine. This value should be noted in the annual system performance evaluation report so that it may be compared when data are obtained at a later date.

Image Intensity Uniformity

The image intensity uniformity test measures the percent image uniformity (PIU) of the image intensity over a large uniform region of the phantom lying near the middle of the imaged volume and thus near the middle of the sensitive region of the volume RF coil.

Head coils, body coils, and some extremity coils are designed for clinical use to have a fairly uniform spatial sensitivity near the middle of the coil when loaded as typical for human body parts. Poor signal uniformity indicates that the coil has significantly greater variation in image intensity than is normal for a properly functioning system. Lack of image intensity uniformity suggests a deficiency in the scanner, often a defective volume coil or problem with the radiofrequency subsystems.

RF Phase Stability

The RF pulses used in MRI are generated using a stable radiofrequency source (radiofrequency synthesizer), which usually works in the coherent (phase locked) mode to assure stability of the generated signal. Multi-slice imaging sequences require rapid switching of the radiofrequency offset. Commonly, the coherence of the synthesized signal can be restored within several microseconds after switching. This feature, combined with high stability of the generated frequency (commonly 10–8 ppm or better) is more than sufficient for most standard MRI applications. The radiofrequency signal is then modulated (most often in amplitude, but frequency and/or phase modulations can be found as well) to generate the appropriate pulses. Radiofrequency output, which is "deficient" in quality, can result in a variety of imaging artifacts depending on the magnitude and type of the defect.

Phase related errors are defined in terms of inappropriate (either increased or decreased) image signal at specified spatial locations. Generally, these artifacts are characterized by increased signal intensity in areas known to

contain no signal producing material. Errors in the application of phase-encoding gradients for imaging and errors in both RF transmit and receive quadrature phases result in unique ghost artifacts.

Phase-encoding ghosts will appear as multiple images (possibly smeared into a column) originating at the true object position but displaced along the phase-encoding axis of the image (perpendicular to the frequency-encoding direction). The presence of these characteristic ghost images will generally identify the two axes; however, the specific orientations should not affect the outcome of the measurement described below.

Surface Coils and Volume Coils

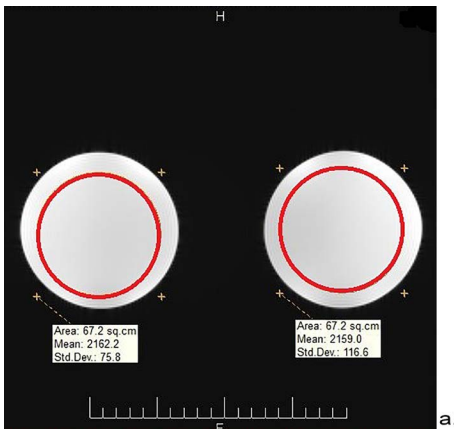
In the following section, strategies that can be used to test all radiofrequency coils used clinically on a particular MRI system are described. The tests are described in two subsections: one for volume coils and the other for surface coils. They differ in the following essential approaches.

For volume coils, three measurements are performed: image uniformity, SNR, and percent signal ghosting. Together, these three parameters can be used to characterize a coil's performance and track changes in RF coil performance. The determination of image uniformity, SNR, and percent signal ghosting may be obtained from a single image. In volume coils, this image should be acquired at the center of the coil and oriented perpendicular to the axis of the coil.

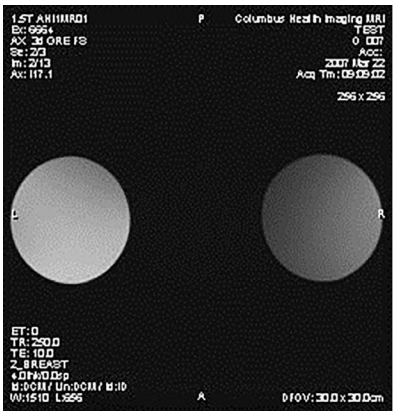
For surface coils, it was previously recommended that the maximum SNR be measured because of the characteristic non-uniform sensitivity patterns of these coils [6,28]. Though appropriate, considerable variations in the maximum SNR will result if the phantom-to-coil positioning and ROI placement for both signal and noise are not carefully recorded and reproduced. Experience has shown that the mean SNR derived using large ROIs for both signal and noise may be more easily reproduced and thus be a more stable indicator of surface coil performance than maximum SNR. For this reason, the revised manual includes both maximum SNR and mean SNR as acceptable alternative performance parameters for surface coils. In either case, images acquired with appropriate uniform phantoms must be visually checked to ensure that there is not excessive ghosting and that there are not uncharacteristic asymmetries in surface coil performance. With surface coils, the appropriate position and orientation must be determined based on the available phantom and the type of clinical studies performed with the specific RF coil. The determination of image orientations and positions is the first task of the qualified medical physicist/MRI scientist in the RF coil evaluation process. A thorough description of each coil setup, the phantom used, and scan parameters employed should be included in the annual performance report. A photograph of the coil and phantom setup is helpful in ensuring consistency from year to year.

For the purpose of this test, flexible coils are considered to be surface coils. For multi-channel coils, it is recommended to test individual channel elements separately.

Breast coils require testing to ensure that all coil elements function properly, that signals are reasonably uniform within each breast, and that signals are comparable between left and right breasts. Bilateral breast coils can be tested using two identically-shaped phantoms containing the same weak paramagnetic solution, each of which fills a large fraction of the sensitive volume of each breast coil as shown in Figure 9.



a.


b.

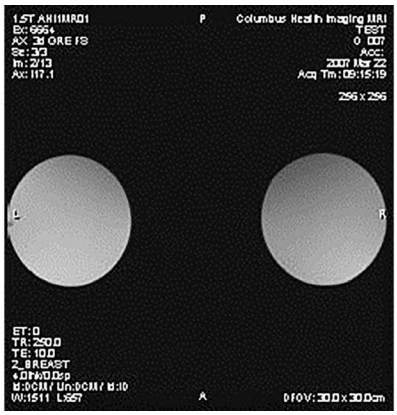

c.

Figure 9. Examples of a pair of identically-shaped and identically-filled cylindrical phantoms imaged coronally in bilateral breast coils. a) Image showing ROIs that indicate similar mean signal values in both coils. b) Example of a 4-channel bilateral breast coil demonstrating significantly lower signal in the medial portion of the right breast coil, due to failure of a single channel of the 4-channel coil. Mean SNR in the right breast coil measured approximately half of that in the left breast coil, with significant non-uniformity within the right coil. c) Identical acquisition to b., when all 4-channels were functioning properly, but with some non-uniformity in the right breast coil.

PHANTOMS

Phantom Characteristics

The phantom should be selected that best simulates the geometry of the body part under investigation.

When imaging a small phantom in body coils, a large volume of conductive solution inside a plastic annulus may have to be placed in the magnet to ensure proper operation. This "body coil loader" simulates the electrical

properties of a human body.

For imaging body parts with surface coils, the selection of phantom geometry may be more difficult. Often, MRI equipment manufacturers provide appropriate phantoms with surface coils for purposes of calibration.

The substance in the phantom should have a T1 value within the range of those found in soft tissues at the scanner's field strength. The phantom should also be designed so that loading of the RF coil is similar to that produced when the coil is in clinical use. The phantom should produce a uniform signal in the region from which uniformity and SNR images are obtained.

The ACR MRI accreditation phantom should be adequate for evaluating head coils, if the images are acquired in an axial orientation. The ACR phantom should be positioned so that the uniformity section, near the center of the phantom, is in the center of the coil. Other phantoms will be necessary for imaging with other volume coils. Breast coils can be tested using an identical pair of 2-liter bottles, one inserted in each side, filled with the same weak paramagnetic solution (e.g., 10 millimolar $NiCl_2$ or $CuSO_4$ with 0.45% NaCl).

Scan Parameters

A T1-weighted scanning series is recommended since these typically do not require a long scan times. The T1-weighted series used for the ACR MRI Accreditation Program (a single spin-echo series, TR = 500 ms, TE = 20 ms) is a good choice since it can be performed readily on almost any scanner.

If the qualified medical physicist/MRI scientist is willing to spend some time customizing the test procedure to the individual scanner, scan times can be reduced. For instance, reducing TR may reduce scan times. Whatever modifications are performed, SNR should be maintained at a value of 20 or greater for the region under investigation. The optimized pulse timing and flip angle parameters should be recorded in the QC procedures manual and used in subsequent measurements.

The FOV shall be chosen appropriately for the RF coil under investigation. The FOV shall be selected so that regions outside the phantom are displayed on the image for background noise measurements. To minimize potential problems with ghosting wrapping around into the phantom, it is preferable, where possible, to choose a FOV that is at least twice the size of the phantom in the phase-encoding direction. When that is not possible, select the largest FOV the magnet supports. The selected FOV should be stated in the QC procedures manual.

The matrix size should be chosen to provide an adequate number of pixels for good signal and noise measurements. A 256 × 256 matrix is typically adequate. The matrix size and FOV shall be consistently applied for QC testing with their value stated in the medical physicist's report and the QC procedures manual.

For single slice measurements, the slice thickness should be chosen to optimize the noise measurement while still providing adequate signal in the phantom. This is typically between 1 mm and 5 mm depending on the field strength. Thinner slices should be used at higher field strengths, thicker slices at lower fields. The slice thickness chosen shall be used consistently and its value stated in the medical physicist's report and the QC procedures manual.

1. Volume Coil Tests

Volume coils encompass the body part to obtain signals relatively uniformly from the tissues within the coil. In superconducting magnets, the axis of this type of coil is generally parallel to the axis of the magnet (parallel to the B_0 magnetic field). In low-field open magnet systems, the axis of the volume RF coil is generally oriented perpendicular to the B_0 magnetic field. Signal-to-noise ratio (SNR), percent image uniformity (PIU), and percent signal ghosting (PSG) are complementary measurements for volume RF coils.

TEST PROCEDURES

1. Position the RF coil in its normal clinical orientation. Place the phantom in an orientation that most closely represents the position of the body part of interest in the clinical scan. Generally, the center of the phantom should be positioned as close to the center of the RF coil as possible.
2. Positioning aids, such as external references on both the coil and the phantom, should be noted and described in the QC procedures manual. The phantom should be marked with stickers or other marks to indicate the position of the RF coil with respect to the phantom. In cases of complex coil geometries, such as shoulder coils, photographs, and/or diagrams may be necessary to ensure that the relationship between the coil and the phantom is reproducible from test to test.
3. Run the pulse sequence with a slice positioned near the center of the RF coil and with the uniform signal-producing volume positioned in the image plane most often used in clinical practice (axial, sagittal, coronal, or oblique).
4. Record all pulse sequence and hardware parameters in the annual system performance evaluation report.

RECORDING SIGNAL MEASUREMENTS

Intensity and gradient distortion correction algorithms can significantly alter image signal and noise. Therefore, when possible it is recommended that these corrections be turned off for SNR measurements even if they are used clinically. A uniform homogeneous phantom should be used. The choice of the specific SNR method is the decision of the qualified medical physicist/MRI scientist; however, it is essential that the same method be used for all measurement comparisons and trend assessments. Below are acceptable methods for measuring SNR.

a. SNR

i. Single-Image SNR Method (SNR_{ACR} or SNR_{NEMA4})

1. Select an image depicting the center of the phantom that is along the central axis of the phantom and is free of any internal structures (Figure 10).
2. Create a "mean signal region of interest" that covers at least 75% of the cross-sectional area of the phantom, as viewed in the image (Figure 10a). This "mean signal ROI" defines the region in which measurements will be performed later for signal uniformity.
3. Record the mean signal, which is the average value of all the pixels in the mean signal ROI, in the annual system performance evaluation report.
4. Place a measurement ROI of as large a size as possible in a position in the background area outside the phantom volume in the frequency-encoding direction (Figure 10b), since regions in the image corrupted by artifacts, such as those often occurring in the phase-encoding direction, should be avoided. This is the "air ROI." One should be careful not to position the air ROI in a region where effects of the RF receiver filter or gradient nonlinearity corrections are noticeable. One should evaluate the background with a low window width and appropriate level setting to display background signal and noise (Figure 10b) to avoid placing the air ROI in an area containing RF leakage or an area where the values have been zeroed by the system. The size of the air ROI should be as large as possible to obtain the best statistics on background signal and noise measurements within the constraints mentioned above.

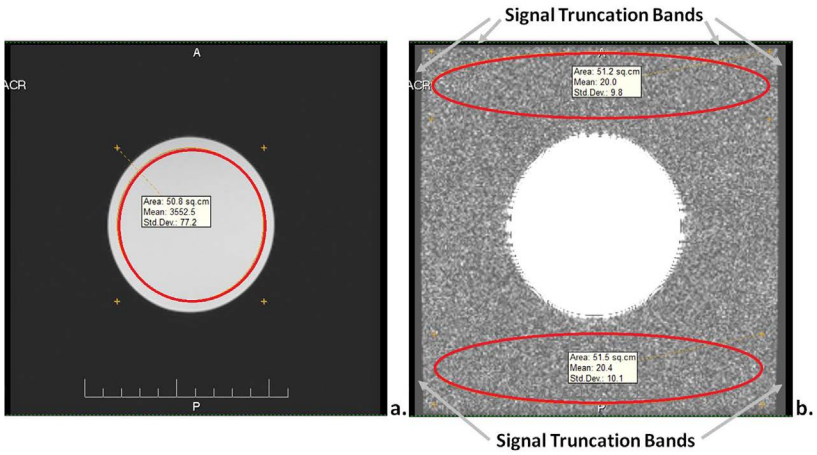


Figure 10. a) ROI placement to determine mean signal in an axial image of a cylindrical phantom in a single-channel knee coil. The phantom was 9 cm in diameter, and the FOV was 20 cm x 20 cm. b) Illustration of appropriate windowing to analyze background signal, determine ROI placement, and perceive signal truncation in the same image as a. Note the thin region of signal truncation along each outer edge of the image FOV where signal has been zeroed (gray arrows). This image, where phase-encoding was left-to-right, shows uniform background signal and noise in the air regions that exclude the truncation bands. Appropriate air ROIs include as much background area as possible in the frequency-encoding directions (above and below the phantom in this case), excluding signal truncation bands at the edges of the image field and signal bleed areas near the phantom, as shown.

The simplest method to assess image noise is to use the standard deviation in the background air ROI. Accurate measurements of image signal or noise require ROIs of at least 1,000 pixels (NEMA MS-1, 2008). If a single background air ROI does not provide an adequate number of pixels, multiple air ROIs, such as the two background ROIs in Figure 10, can be combined. Standard deviations from multiple ROIs can be combined in quadrature:

$$\text{For n ROIs: } \sigma_{combined} = \sqrt{(\sigma_1^2 + \sigma_2^2 + \cdots + \sigma_n^2)/n}$$

It is important that each ROI included be of similar area, as combining signal standard deviation ROIs in quadrature attributes equal weight to each ROI, regardless of area. It is also important that each background ROI included be free from artifacts, signal filtering, and other confounding influences, as described above. This means that to get an accurate measurement of background noise, all air ROIs should be placed in the frequency-encoding direction and be free from artifacts and filtering effects.

5. SNR_{ACR} is calculated by dividing the mean signal in the phantom by the standard deviation in the air ROI:

$$SNR_{ACR} = (Mean\ Signal\ in\ Phantom)/\sigma_{air}$$

Record this value in the annual system performance evaluation report.

6. For a single-channel coil, mean signal and standard deviation in the air ROI should be related by the expression [22,24]:

$$S_{air} = (1.913)\,\sigma_{air}$$

This relationship between S_{air} and σ_{air} applies for single-channel coils when the air ROI has been placed appropriately in a region in the frequency-encoding direction that is free from RF receiver filter corrections, gradient nonlinearity corrections, artifacts, and background signal truncation. Finding this approximate relationship between background signal and standard deviation can be used as a check that ROI placement is reasonable and that the measurement is free from the effects mentioned above.

On some scanners, signal or noise filtering is beyond the control of the medical physicist/MRI scientist, and this theoretical relationship between signal and its standard deviation in the background ROI will not apply. The relationship shown above between S_{air} and σ_{air} applies only to single-channel coils. For multichannel phased-array RF coils, the relationship between background signal and background standard deviation depends on the number of channels being combined [24].

In cases where σ_{air} is very low (i.e., less than about 4), signal truncation due to digitization can adversely affect the accuracy of noise measurements. In such cases, more reliable measurements of σ_{air} can be made by increasing air standard deviation values to greater than 4 so that a truncation error during signal digitization does not adversely affect noise measurement. This can be done by decreasing the voxel volume (either by decreasing the slice thickness, increasing the matrix for the same FOV, or both), by decreasing TR, by increasing the bandwidth, or with some combination of these modifications to the acquisition pulse sequence. To avoid inducing signal nonuniformities, TR values should not be decreased below about 200 ms for spin-echo sequences.

7. For a single-channel coil, SNR_{ACR} is related to SNR_{NEMA4} by a constant multiplicative factor:

$$SNR_{NEMA4} = \frac{Mean\ Signal}{\frac{\sigma_{air}}{\sqrt{2-\frac{\pi}{2}}}} \approx 0.655 \times \frac{Mean\ Signal}{\sigma_{air}} = 0.655 \times SNR_{ACR}$$

8. The factor of $\sqrt{2-\frac{\pi}{2}} = 0.655$ corrects for the fact that the MR background signal has a Rayleigh distribution, not a Gaussian distribution [22]. The important issue is not the multiplicative factor, but the fact that SNR is measured in a consistent, repeatable, and reliable manner, with an adequately large FOV and adequately large background ROIs placed in the frequency-encoding direction each time SNR measurements are made. Consistent image acquisition and measurement methods are needed to ensure that SNR is a reliable metric of RF coil performance over time.

Record the SNR value in the annual system performance evaluation report.

ii. Two-Image SNR Method (SNR_{NEMA1})

1. Acquire two identical images of a uniform homogeneous phantom (Figure 11). The two images should be acquired during the same imaging session with a minimal time interval between.

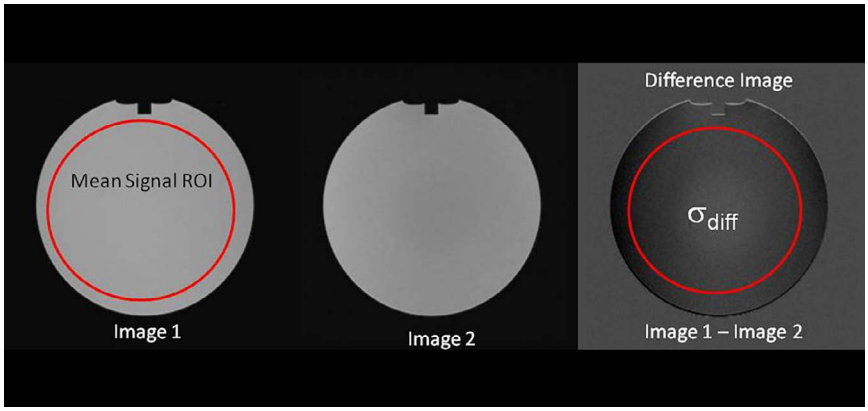


Figure 11. NEMA Method 1: two-image difference method for measuring SNR.

2. In either one of the two images, create a "mean signal region of interest" that covers at least 75% of the cross-sectional area of the phantom as viewed in the image.
3. Record the mean signal, which is the average of all the pixels in the mean signal ROI, in the annual system performance evaluation report.
4. Create the "difference image" by subtracting the two images. Note that some scanners do not provide the operator with the tool needed to produce the difference image, thus the NEMA Method 1 technique will not be practical unless the images are taken to another workstation that permits image subtraction. If the NEMA Method 1 approach is not practical, the single-image method, described above, should be used.
5. In the difference image, create similar ROIs as in step 2 to define the mean signal and determine the standard deviation of the difference image (σ_{diff}).
6. Record σ_{diff}, the standard deviation of the pixels in the difference image ROI, in the annual system performance evaluation report.
7. SNR_{NEMA1} is calculated by multiplying the mean signal by the factor $\sqrt{2}$ (to account for the noise in two subtracted images adding in quadrature) and then dividing by the noise standard deviation of the difference image (σ_{diff}).

$$SNR_{NEMA1} = \sqrt{2}\,\frac{Mean\ Signal}{\sigma_{diff}}$$

8. Record the SNR value in the annual system performance evaluation report.

b. Percent Image Uniformity (PIU)

1. Referring back to Figure 10a, set the window width to a small value (e.g., 1). Adjust the window level so that the region of greatest signal intensity is depicted with only a few bright pixels within the large "mean signal ROI" as shown in Figure 12a.
2. Create a "measurement ROI" that is approximately 0.15% of the area of the FOV, e.g., approximately 1 cm^2 for a 25 cm × 25 cm FOV.

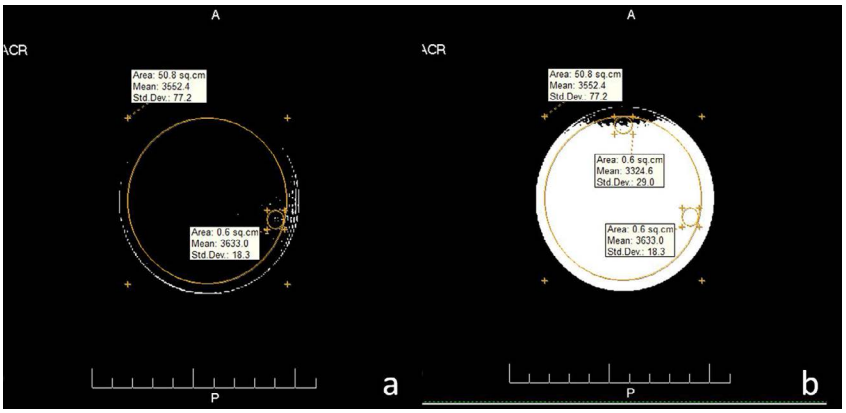


Figure 12. Evaluation of percent image uniformity in the same knee coil and phantom shown in Figure 10. a) Appropriate windowing and ROI placement for determination of maximum signal within the large ROI using the small ROI centered on the few bright pixels on the right. b) Appropriate windowing and ROI placement for determination of minimum signal within the large ROI using the small ROI centered on the dark pixels at the top.

3. Move the measurement ROI to the position of greatest signal intensity that is within the mean signal ROI (i.e., covering the largest number of bright pixels within the mean signal ROI).
4. Determine the mean signal value of all the pixels in the small measurement ROI. This is the maximum signal (max ROI). Record the value in the annual system performance evaluation report.
5. In a similar manner as steps 1–3, lower the window level so that only a few dark pixels are displayed within the large mean signal ROI and create a similar sized small ROI over the lowest signal intensity within the mean signal ROI, as shown in Figure 12b.
6. Record this minimum signal (min ROI) value in the annual system performance evaluation report.

7. The PIU is calculated by using the following formula with max and min ROIs:

$$PIU = 100 \times \left(1 - \frac{Max\ ROI - Min\ ROI}{Max\ ROI + Min\ ROI}\right)$$

8. Record this value in the annual system performance evaluation report.

c. Percent Signal Ghosting (PSG)

1. Establish measurement ROIs in the four positions as shown in Figure 13 outside of the phantom volume (left, right, top, and bottom).
2. Record each of the four measured mean signal values (left, right, top, and bottom) in the annual system performance evaluation report.
3. The PSG) is calculated by using the following formula:

$$PSG = 100 \times \left|\frac{(Left + Right) - (Top + Bottom)}{(2 \times Mean\ Signal)}\right|$$

4. Record this value in the annual system performance evaluation report.

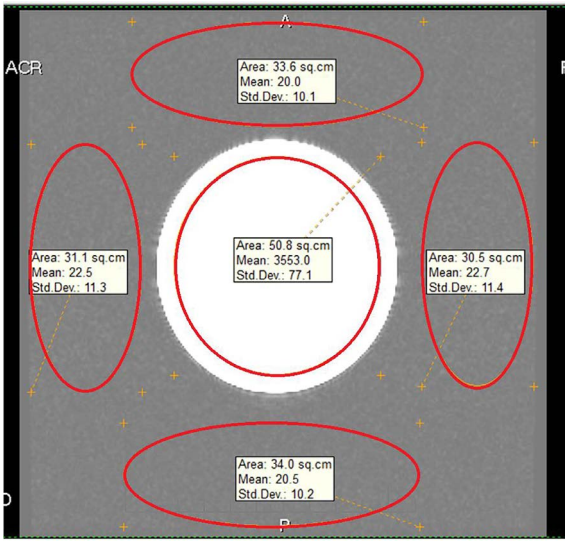


Figure 13. Placement of ROIs inside and outside the phantom to determine percent signal ghosting.

2. Surface Coil Tests

Surface coils are generally designed to receive signals from different regions of the body. Thus, in evaluating these devices, one should select a uniform volume of a phantom to demonstrate variations in uniformity of signal produced by a given coil. The volume of investigation should have relaxation times and RF coil loading properties similar to living tissue. Most manufacturers provide phantoms for testing complex surface coil systems.

The phantom should be permanently marked so that the surface coil can be accurately positioned for successive measurements. Use only phantoms that will be permanently stored at the site. Allow about five minutes for the solution in the phantom to settle down before starting the SNR scan (prescan routines can be performed during this time).

TEST PROCEDURE

a. SNR Surface Coil (maxSNR)

1. Select an image depicting the center of the phantom that lies along the central axis of the phantom and is free of any internal structures (Figure 14a).
2. Set the window width to a small value so that signal variations within the phantom are visible. Adjust the window level so that the region of greatest signal intensity is depicted.
3. Create a "measurement ROI" with an area of at least $1cm^2$.
4. Move the measurement ROI to the position of greatest signal intensity within the phantom.
5. Determine the mean signal value in the small measurement ROI. The ROI should be positioned so that it does not include any obvious artifacts. This is the maximum signal. Record the value in the annual system performance evaluation report.
6. Place a large measurement ROI outside of and away from the phantom in the frequency-encoding direction, since regions in the images corrupted by artifacts should be avoided. This is the "noise ROI." The noise ROI should be carefully positioned in a region where the effects of the RF receiver filter, ghosting or other artifacts are avoided (see Figures 14a and 14b). The noise ROI should be made as large as possible to improve sampling statistics while minimizing the effect of artifacts.
7. Determine the noise as the standard deviation (i.e., the root mean square signal value) in the noise ROI located in the image background (σ_{air}). Record the value in the annual system performance evaluation report.

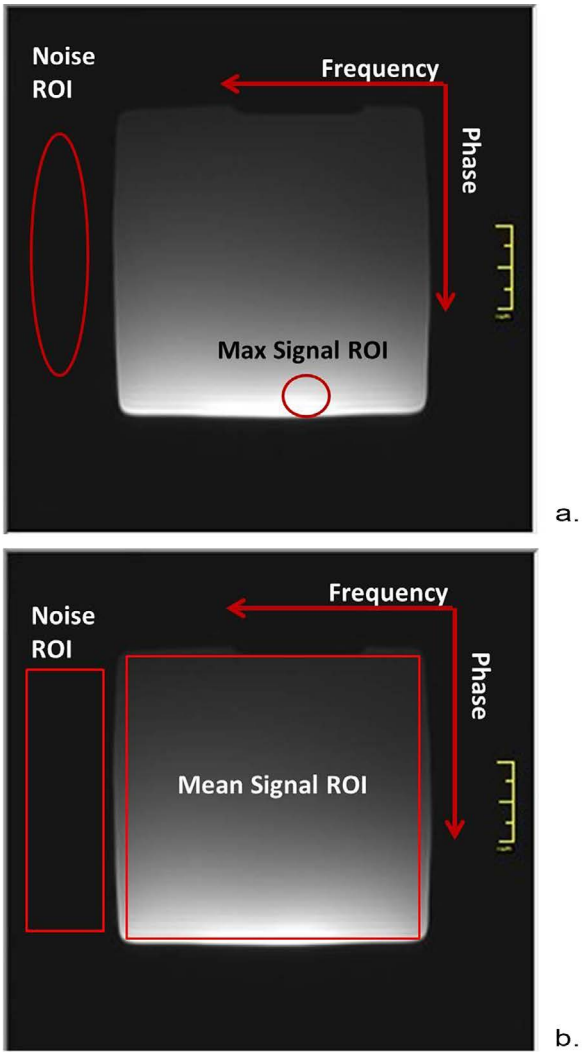


Figure 14. Axial image of a uniform phantom acquired with an 8-channel spine coil. Noise ROI chosen in the background in the frequency-encoded axis. a) Image illustrating ROI placement to be used when estimating the maximum SNR. b) Image illustrating ROI placement when estimating the mean SNR.

8. The maximum SNR is calculated by dividing the maximum signal within the phantom by the standard deviation measured outside of the phantom, σ_{air}:

$$maxSNR = (Max\ Signal\ in\ Phantom)/\sigma_{air}$$

Record this value in the annual system performance evaluation report.

9. Observe the signal intensity distribution and note on the annual system performance evaluation report whether it generally appears the same as when previous measurements were performed on this coil. Save a copy of the image and record the window width and window level settings for future reference.

10. Observe the image and note on the annual system performance evaluation report whether image ghosting appears to be unusually high. If ghosting does appear high, measure the PSG as described above in Section IV.D.1.c (volume coil PSG measurements).

b. SNR Surface Coil (MeanSNR)

1. Select an image depicting the center of the phantom that lies along the central axis of the phantom and is free of any internal structures (Figure 14b).
2. Create a "mean signal region of interest" that covers as much of the cross-sectional area of the phantom as possible, as shown in Figure 14b.
3. Record the mean signal, which is the average value of all pixels in the mean signal ROI, in the annual system performance evaluation report.
4. Place a measurement ROI of as large a size as possible in a position in the background area outside the phantom volume in the frequency-encoding direction (Figure 14b), specifically avoiding regions in the image corrupted by artifacts, such as those often occurring in the phase-encoding direction. This is the "air ROI." The air ROI position should also avoid regions where the effects of the RF receiver filter or gradient nonlinearity corrections are noticeable. One should evaluate the background with a low window width and appropriate level settings to display background signal and noise to avoid placing the air ROI in an area containing RF leakage or an area where the values have been zeroed by the system. The size of the air ROI should be as large as possible to obtain the best statistics on background signal and noise measurements within the constraints mentioned above.
5. Image noise is defined to be the standard deviation in the background air ROI.
6. The mean SNR for the surface coil is calculated by dividing the mean signal in the phantom by the standard deviation in the air ROI:

   $$\textit{mean SNR} = \textit{(Mean Signal in Phantom)}/\sigma_{air}$$

   Record this value in the annual system performance evaluation report.

3. RF Array Coils

TEST PROCEDURE

RF array coils are closely coupled coils that work together, each with their own RF channel, to produce more uniform signal over an extended or irregular body part. A spine array, for example, includes sections that collectively can image the entire spine at once or sets of adjacent individual elements that can be selected to acquire images over a more restricted section of the spine, such as a cervical spine, thoracic spine,

or lumbar spine. It is recommended that the qualified medical physicist/MRI scientist perform a more detailed assessment of coil performance by measuring SNR for each element of an RF array coil in a manner similar to the surface coil SNR assessment. This test may require special settings prior to image acquisition or access to the service functions of the system so that separate images of each independent RF channel can be acquired and displayed. If assessment of individual coil elements is not possible, the single-image method described below can be used to assess multichannel array coils. For more details regarding RF array coils see Glockner et al [29].

The single-image method of SNR determination described above for single-channel coils can be extended to multichannel phased-array coils based on the methods of Constantinides et al [24]. As for single-channel coils, phase-array coils ideally should be imaged with a FOV at least twice the size of the phantom used or, alternatively, with the largest FOV permitted on the system.

1. Select an image depicting the center of the phantom that lies along the central axis of the phantom and is free of any internal structures (Figure 15).
2. Create a "mean signal region of interest" that covers as much of the cross-sectional area of the phantom as possible, as shown in Figure 15a.

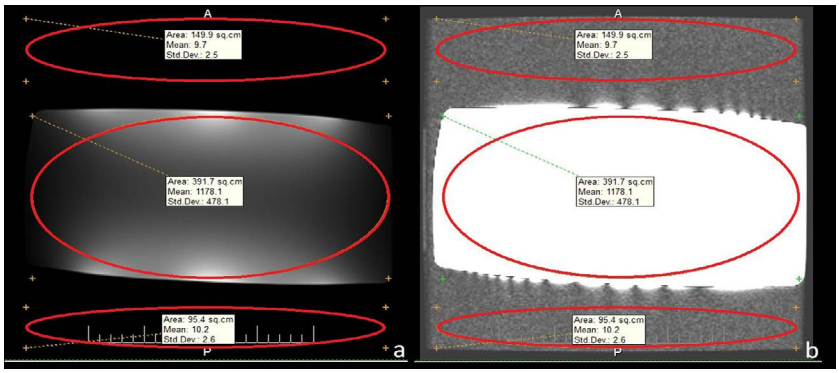


Figure 15. Axial image of a uniform phantom of a near-rectangular cross-section to test a 4-channel cardiac surface coil. a) Window width and level have been set to display signal nonuniformities within the phantom and to place the large ROI for mean signal measurement within the phantom. b) The same image with window width narrowed and level adjusted to better display background signal and noise. Air ROIs have been placed outside the phantom to measure mean and standard deviation values in the background. Signal within the phantom and standard deviation in air are used to determine mean SNR for this surface coil, as described by method b. above. Consistency of such SNR measurements from survey to survey, along with similar measurements of each coil channel individually, is the best way to assess that the entire coil works properly.

3. Record the mean signal, which is the average value of all the pixels in the mean signal ROI, in the annual system performance evaluation report.

4. Place a measurement ROI of as large a size as possible in position in the background area outside the phantom volume in the frequency-encoding direction (Figure 15b), since regions in the image corrupted by artifacts should be avoided. This is the "air ROI". One should be careful not to position the air ROI in a region where effects of the RF receiver filter or gradient nonlinearity corrections are noticeable. One should evaluate the background with a low window width and appropriate level setting to display background signal and noise (Figure 15b) to avoid placing the air ROI in a an area containing RF leakage or an area where the values have been zeroed by the system. The size of the air ROI should be as large as possible to obtain the best statistics on background signal and noise measurements within the constraints mentioned above. If a single air ROI does not provide an adequate number of pixels (i.e., at least 1,000), multiple ROIs, such as the two background ROIs in Figure 15, can be combined. Standard deviations from multiple ROIs can be combined in quadrature.

   For n ROIs: $\sigma_{air} = \sqrt{(\sigma_1^2 + \sigma_2^2 + \cdots + \sigma_n^2)/n)}$

   It is important that each ROI included be of similar area, as combining standard deviation ROIs in quadrature attributes equal weight to each ROI, regardless of size. It is also important that each background ROI included be free from artifacts, signal filtering, and other confounding influences.

   As with single-channel coils, more reliable measurements of σ_{air} can be made by taking steps to ensure that air standard deviation values are above about 4, so that signal truncation during digitization does not adversely affect noise measurements. This can be done by decreasing the voxel volume (either by decreasing the slice thickness or increasing the matrix for the same FOV, or both), by decreasing TR, by increasing the bandwidth, or with some combination of these adjustments. To avoid inducing signal nonuniformities, TR values should not be decreased below 200 ms for spin-echo sequences.

   SNR is calculated by dividing the mean signal in the phantom by the true noise standard deviation, σ_{true}:

   $$SNR = (Mean\ Signal\ in\ Phantom)/\sigma_{air}$$

   Note that this SNR differs from SNR_{ACR}. For single-channel coils, this definition of SNR is equal to SNR_{NEMA4}.

SUGGESTED PERFORMANCE CRITERIA AND CORRECTIVE ACTIONS – ALL COILS

Factors contributing to variations in SNR include (i) general system calibration (resonance frequency, flip angles, etc.), (ii) gain, (iii) coil tuning, (iv) RF shielding, (v) coil loading, (vi) image processing, (vii) scan parameters, and (viii) phantom positioning.

A general lack of image intensity uniformity indicates a deficiency in the scanner, often a defect in the RF subsystems. Sometimes pieces of metal can get lost in the head coil or pieces of the RF coil can become dislodged within the coil housing. These can cause alterations of the distribution of the RF magnetic field.

Failure of coil components can affect coil impedance and may result in degradation of image uniformity and SNR. Magnitude-reconstructed images are commonly used in clinical MRI because they are relatively immune to phase errors in the MR signals. When the phase errors become large, they can result in ghosting and magnitude image. Ghosting is a very nonspecific indication of a MRI system problem. In general, it is caused by receiver, transmitter, or gradient fluctuations.

Ghosting can also be caused by motion or vibration of the phantom during the scan. Make sure that coils and phantoms are secured and are not free to move during scanning.

Receivers on older systems that used analog components, particularly in mixing and filtering stages, may have ghosts due to quadrature receiver imbalance [30,31]. This ghosting is usually distinguished from other ghosting since there will be one ghost, and it will be reflected through the origin of the volume of interest. Thus, an object in the upper right corner of one slice will produce quadrature ghosts in the lower left corner of another slice at an equal distance from the center of the image. The service engineer recalibrating quadrature channels of the receiver coil can eliminate quadrature ghosts.

Periodic amplitude inconsistencies can result in easily identifiable types of ghosting. A "half FOV ghost" or "N/2 ghost" is common in single-shot EPI images and is difficult to eliminate entirely.

ACTION CRITERIA FOR ALL COILS

Action criteria should be determined by the qualified medical physicist/MRI scientist taking into account the particular features of each piece of equipment; however, simple guidelines should be followed.

Values of SNR vary greatly with MRI system type. The range of acceptable measurements should be determined at the time of the acceptance testing and/or by taking several baseline measurements and setting the action limits at ± one standard deviation.

Head coils and other volume coils designed for clinical use have fairly uniform spatial sensitivity near the middle of the coil when loaded as typical for human tissue. In head coils, PIU values less than 90% are uncommon for a properly functioning system. It should be noted that for multielement array coils, application of an image intensity correction algorithms may be necessary. The ACR MRI Accreditation Program requires that PIU of the head coil be 87.5% or greater for systems of 1.5T or below, and 82% or greater for 3T systems.

Ghosting ratios should be less than 2.5% using the head coil in T1-weighted spin-echo scans.

SUMMARY

This section has described a set of tests for monitoring RF coil performance. It may be desirable to compare SNR and uniformity among various RF coils. Note that the same imaging pulse sequence parameters may be used for obtaining data on all RF coils. The data for these RF coils also may have been obtained using various phantoms with different filling solutions. Be careful to allow for the differences among the relaxation and loading properties of phantoms with different filling solutions. Using phantoms with solutions that are identical in terms of relaxation times and conductivity allows for the most direct comparison of performance among various RF coils.

MRI service engineers have a set of diagnostic tests to determine whether the RF coils are functioning properly. Often, when a defect is detected the RF coil cannot be repaired on-site and must be replaced with another coil specific to the anatomy of interest.

E. Soft-Copy (Monitor) Quality Control

OBJECTIVE

A soft-copy QC program should be in place for all diagnostic workstations. The specifications for such a QC program are outside the scope of this document. However, at a minimum, the scanner console monitor and any on-site technologist workstation, if applicable, should be included in the annual system performance evaluation. For more information on soft-copy display QC, please refer to AAPM TG 18: Online report N.03, Assessment of Display Performance for Medical Imaging Systems.

At acceptance testing, display devices are tested to ensure that they meet the manufacturer's published specifications for 1) maximum and minimum luminance, 2) luminance uniformity, 3) resolution, and 4) spatial accuracy. Measurements of the monitor's performance should be made at regular intervals thereafter using the techniques described below or methods described in AAPM TG 18.

In general, soft-copy display device quality control is defined in accordance with DICOM Part 14. Currently, images are presented from the scanner to the diagnostic workstation and scanner console monitors as raw pixel values, but MRI system manufacturers do not provide the images with an associated "presentation look-up table."

TEST PROCEDURE

Without full implementation of the DICOM Part 14 Standard, the following limited set of tests is recommended. (In addition, the qualified medical physicist/MRI scientist is referred to the report of Task Group 18 of the Diagnostic X-Ray Imaging Committee of the American Association of Physicists in Medicine for more thorough and standardized soft-copy display tests [32]). If a scanner is fully DICOM Part 14 compliant, then additional tests, such as luminance response can be carried out ([33,34]).

1. Maximum and Minimum Luminance

a. Measure monitor luminance using a precise luminance meter. Record the data for the luminance meter in the annual system performance evaluation report.

b. Measurements are performed on a monitor screen when the image displays are at their brightest levels. Set the window width and window level to their minimum values so that the monitor is uniformly at its brightest value.

c. Measure the luminance in the center and at each of the four corners of the image display area. Record these maximum luminance values in the annual system performance evaluation report.

d. Measurements are also performed in the same manner on the monitor screen when the image display is at its darkest level. Set the window width to its minimum value and window level so that the monitor is uniformly at its darkest value. These minimum luminance values should also be recorded in the annual system performance evaluation report.

2. Luminance Uniformity

Calculate the percent difference of the brightest luminance values measured in the image display area, using the following equation:

$$\%\ difference = 200 \times \frac{L_{max} - L_{min}}{L_{max} + L_{min}}$$

Where L_{max} and L_{min} are the maximum and minimum measured luminance values, respectively, for the measurements taken with the monitor at its brightest level (AAPM TG18: On-line report No. 03, Assessment of Display Performance for Medical Imaging Systems).

Record this value in the annual system performance evaluation report.

3. Resolution, Linearity, Contrast, and Distortion

The qualified medical physicist/MRI scientist should view the "SMPTE" pattern on the monitor while positioned directly in front of the image display and at least 50 cm from the monitor surface. The SMPTE pattern should be evaluated as follows:

a. The 0–5% contrast pattern should be visible.

b. The 95–100% contrast pattern should be visible.

c. Each gray-level step from 0% to 100% should be distinct from adjacent steps.

d. The borders and lines of the SMPTE pattern should be straight.

e. There should be no distortion or misalignment using the grids across the screen (linearity).

f. Alphanumeric characters should be sharp (in focus).

g. The high contrast line-pair images (each line in vertical and horizontal stripes) in the squares at the center and in the corners should be distinct without magnification.

h. There should be no streaking in and around the white rectangles and the black rectangles.

Record observations as "comments" in the annual system performance evaluation report.

4. Spatial Accuracy

Typically, a SMPTE test pattern that displays a rectangular grid is displayed with a magnification factor that allows it to fill the entire screen. A similar grid pattern is laid over the screen and compared to the displayed image. Record observations as "comments" in the annual system performance evaluation report.

SUGGESTED PERFORMANCE CRITERIA AND CORRECTIVE ACTION

Maximum and minimum luminance: The maximum brightness of diagnostic quality monitors should exceed 90 Cd/m^2, and the minimum brightness values should be less than 1.2 Cd/m^2.

Luminance uniformity: The calculated % difference in the maximum luminance values should be ≤ 30%.

The resolution, linearity, contrast, and distortion criteria described above should be met.

For more details regarding evaluation of the SMPTE test pattern, see Medical Physicist/MRI Scientist's Appendix, Section VI.C.

F. MR Safety Program Assessment

OBJECTIVE

To minimize risks in the MR environment to patients, health care professionals, and any others that may encounter the fields of the MR scanner, each site must establish, implement, and maintain current safety policies and procedures. Information regarding establishment of a quality MR safety program can be found in the ACR Guidance Document for Safe MR Practices: 2013 [35]. The hazards in the MRI suite maybe divided into three categories: 1) facility design, 2) operational, and 3) clinical. Facility design refers to the facility layout in which zones are identified with appropriate signage and strategies for controlled access. Operational refers to procedures for screening both personnel and objects that may be introduced to the MR suite. Clinical refers to procedures that can be used to determine the MR safety and compatibility of implants and other medical devices.

METHOD

At the time of the annual performance testing, the qualified medical physicist/MRI scientist must review the site's written safety policies and determine that the written policies are readily accessible to facility staff. The categories listed below should be addressed in the policies.

- Designated MR medical director
- Site access restrictions (MR zones)
- Documented MR safety education/training for all personnel
- Patient and non-MR personnel screening
- Pediatric patients
- Magnet quench
- Cryogen safety
- Acoustic noise
- Pregnant patients and staff
- Contrast agent safety
- Sedations
- Thermal burns
- Emergency code procedures
- Device and object screening
- Designation of MR safe/MR conditional status
- Reporting of MR safety incidents or adverse incidents
- Patient communication
- Infection control and medical waste

CRITERIA FOR COMPLIANCE

1. Written policies and procedures are present and are being reviewed and updated on a regular basis.
2. Facility has appropriate signage and methods of controlled access.
3. Documentation of regular MR safety training for all MR-designated personnel.

REFERENCES

1. American College of Radiology. ACR-AAPM technical standard for diagnostic medical physics performance monitoring of magnetic resonance imaging (MRI) equipment. Available at: http://www.acr.org/~/media/ACR/Documents/PGTS/standards/MonitorMRIEquipment.pdf Published 2014. Accessed March 1, 2015.
2. National Electrical Manufacturers Association. *NEMA-MS-1. Determination of SNR in Diagnostic Magnetic Resonance Images*. Rosslyn, VA: NEMA; 2008.
3. National Electrical Manufacturers Association. *NEMA-MS-2. Determination of Two-Dimensional Geometric Distortion in Diagnostic MR Images*. Rosslyn, VA: NEMA; 2008.
4. National Electrical Manufacturers Association. *NEMA-MS-3. Determination of Image Uniformity in Diagnostic Magnetic Resonance Images.* Rosslyn, VA: NEMA; 2008.
5. National Electrical Manufacturers Association. *NEMA-MS-5. Determination of Slice Thickness in Diagnostic Magnetic Resonance Images*. Rosslyn, VA: NEMA; 2010.
6. National Electrical Manufacturers Association. *NEMA-MS-6. Determination of Signal-To-Noise Ratio and Image Unifomity for Single-channel, Non-volume Coils in Diagnostic Magnetic Resonance Imaging (MRI)*. Rosslyn, VA: NEMA; 2008.
7. National Electrical Manufacturers Association. *NEMA-MS-9. Characterization of Phase Array Coils For Diagnostic Magnetic Resonance Images*. Rosslyn, VA: NEMA; 2008.
8. American Association of Physicists in Medicine. *AAPM Report No. 100: Acceptance Testing and Quality Assurance Procedures for Magnetic Resonance Imaging Facilities*. College Park, MD: AAPM; 2010.
9. American College of Radiology. *Site Scanning Instructions for Use of the MR Phantom for the ACR MRI Accreditation Program*. Reston, VA: ACR; 1997.
10. American College of Radiology. *Phantom Test Guidance for the ACR MRI Accreditation Program*. Reston, VA: ACR; 1998.
11. American College of Radiology. *Site Scanning Instructions for Use of the Small MRI Phantom for the ACR MRI Accreditation Program*. Reston, VA: ACR; 2008.
12. American College of Radiology. *Phantom Test Guidance for Use of the Small MRI Phantom for the MRI Accreditation Program*. Reston, VA: ACR; 2008.
13. Hoult DI, Lauterbur PC. The sensitivity of the zeugmatographic experiment involving human samples. *Journal of Magnetic Resonance*. 1979;34:425-433.
14. Price RR, Axel L, Morgan T, et al. Quality assurance methods and phantoms for magnetic resonance imaging: report of AAPM Nuclear Magnetic Resonance Task Group No. 1. (AAPM Report No. 28). *Medical Physics*. 1990;17(2):287-295.
15. Kraft KA, Fatouros PP, Clarke GD, Kishore PRS. An MRI phantom material for quantitative relaxometry. *Magnetic Resonance in Medicine*. 1987;5:555-562.

16. Redpath TW, Wiggins CJ. Estimating achievable signal-to-noise ratios of MRI transmit-receive coils from radio-frequency power measurements: applications in quality control. *Physics in Medicine and Biology*. 2000;45:217-227.

17. Moerland MA, Beersma R, Bhagwandien R, Wiljrdeman HK, Bakker CJG. Analysis and correction of geometric distortions in 1.5T magnetic resonance images for use in radiotherapy treatment planning. *Physics in Medicine and Biology*. 1995;40:1651-1664.

18. Bakker CJG, Moreland MA, Bhagwandien R, Beersma R. Analysis of machine-dependent and object-induced geometric distortion in 2DFT MR imaging. *Magnetic Resonance Imaging*. 1992;10:597-608.

19. Vlaardingerbroek MT, den Boer JA. *Magnetic Resonance Imaging*. 2nd ed. Berlin: Springer-Verlag; 1999.

20. Haacke EM, Brown RW, Thompson MR, Venkatesan MR. *Magnetic Resonance Imaging: Physical Principles and Sequence Design*. New York, NY: Wiley-Liss; 1999.

21. Chen HH, Boykin RD, Clarke GD. Routine testing of magnetic field homogeneity on clinical MRI systems. *Medical Physics*. 2006;33:4299-4306.

22. Henkelman RM. Measurement of signal intensities in the presence of noise in MR images [published correction appears in *Medical Physics*. 1986;13:544]. *Medical Physics*. 1984;12:232-233.

23. Gudbjartsson H, Patz S. The Rician noise distribution of noisy MRI data. *Magnetic Resonance in Medicine*. 1995;34:910-914.

24. Constantinides CD, Atalar E, McVeigh ER. Signal-to-noise measurements from magnitude images in NMR phased-arrays. *Magnetic Resonance in Medicine*. 1997;38:852-857.

25. Kaufman L, Kramer DM, Crooks LE, Ortendahl DA. Measuring signal-to-noise ratios in MR imaging. *Radiology*. 1989;173:265-267.

26. Sijbers J, den Dekker AJ, van Audekerke J, Verhoye M, van Dyck D. Estimation of the noise in magnitude MR images. *Magnetic Resonance Imaging*. 1998;16:87-90.

27. Firbank MJ, Coulthard A, Harrison RM, Williams ED. A comparison of two methods for measuring the signal-to-noise ratio on MR images. *Physics in Medicine and Biology*. 1999;44:N261-N264.

28. American College of Radiology. *Magnetic Resonance Imaging Quality Control Manual*. Reston, VA: ACR; 2004.

29. Glockner JF, Hu HH, Stanley DW, et al. Parallel MR imaging: a user's guide. *Radiographics*. 2005;25:1279-1297.

30. Chen CN, Hoult DI. *Biomedical Magnetic Resonance Technology*. Boca Raton, FL: CRC Press; 1989.

31. Holland GN, MacFall JR. An overview of digital spectrometers for MR imaging. *Journal of Magnetic Resonance Imaging*. 1992;2:241-246.

32. Samei E, Badano A, Chakraborty D, et al. *Assessment of Display Performance For Medical Imaging Systems, Report of the American Association of Physicists in Medicine (AAPM) Task Group 18. AAPM On-Line Report No. 03*. Madison, WI: Medical Physics Publishing; 2005.

33. Shepard SJ. Calibration and quality control of digital hard and soft copy display devices on a PACS network. In: *Quality Assurance for the Third Millennium* [CD-ROM]. Strakshall G, Jackson E, eds. College Park, MD: Southwest Chapter AAPM; 2000.

34. Van Metter R, Zhao B, Kohn K. The sensitivity of visual targets for display quality assessment. *Proceedings of SPIE*. 1999;3658:254.

35. Kanal E, Barkovich A, Bell C, et al. ACR guidance document on MR safe practices: 2013. *Journal of Magnetic Resonance Imaging*. 2013;37(3):501-530.

APPENDIX

A. MRI Equipment Evaluation Summary Form

The MRI Equipment Evaluation Summary Form is provided to facilitate the communication of test results to the facility managers. An Excel version of this form, along with the MR Safety Checklist in another tab, can be accessed here. MR Equipment Evaluation Summary Form.

The medical physicist/MR scientist may use any data report format as long as the required information is present. Regardless of forms used, the medical physicist's report must include a pass-fail summary of tests performed and a summary of recommendations to the facility.

B. MRI Safety Program Assessment Checklist

Access the MRI Safety Program Assessment Checklist.

C. Hard-Copy (Film) Quality Control Operating Levels

ESTABLISHING OPERATING LEVELS

The qualified medical physicist/MRI scientist should participate in 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 is responsible for comparing films against the established operating levels. This is done weekly to ensure consistent film quality (MRI Technologist's Section V).

The qualified medical physicist/MRI scientist should seek the participation of the supervising radiologist and film printer system service engineer.

1. Have the service engineer confirm that the film printer is performing within manufacturer's specifications. Running the manufacturer's diagnostic tests should do this.
2. If the film system has a wet-process film processor, make sure the chemicals are fresh, it is operating at the correct temperature, and it is operating with the correct developer and fixer replenishment rates. Correct temperature and replenishment rates are those specified in the film manufacturer's written literature. The service engineer should be asked to assist with this if needed.
3. At the filming console, adjust the monitor brightness and contrast settings according to the manufacturer's recommended procedure.
4. Be sure there is low ambient light and that there is no glare on the screen when making these adjustments. The lighting conditions should be the same as that used for routine filming.

5. Often the controls for monitor brightness and contrast are hidden inside the console and not accessible to the user. If there is any doubt about the correct procedure, or if the controls are not accessible, have the service engineer make the adjustments.

6. Display the SMPTE test pattern (MRI Technologist's Section V) on the filming console. Set the display window and level to the manufacturer-specified values for the SMPTE pattern on this console.

7. It is important to find out from the manufacturer's documentation or from the service engineer the correct window and level values for the SMPTE pattern on the particular display being used. Do not set the window and level by eye. Doing so invalidates this procedure.

8. Examine the SMPTE pattern to confirm that the gray-level display on the filming console is subjectively correct.

   One should see an even progression of gray levels around the ring of gray-level patches. The patch should appear fully black, and the 100% patch should appear bright white. 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 patches around the ring of gray levels are distinct from their neighbors.

   On some displays, the 5% patch may be just barely discernible in the 0/5% patch. That is acceptable. If it cannot be seen at all, that is unacceptable. Normally the 95% patch is easy to discern in the 95%/100% patch.

   If these conditions are not met, it is necessary to correct the problem before continuing with this procedure. Most often, the problem is poor adjustment 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. If so, seek assistance from the service engineer.

9. Film the SMTPE pattern. Use a 6-on-1 format and capture the pattern into all six frames.

10. Visually compare the filmed SMPTE pattern grayscale densities on a viewbox to the monitor displaying the same image with the same window and level settings. Make necessary film printer adjustments to match the film to the monitor appearance, using the manufacturer's recommended procedures. If you are unsure how to do this, obtain assistance from the service engineer.

11. Film several patient images representative of the studies normally done with this scanner. With the supervising radiologist, compare these patient images printed on film and displayed on the monitor, being careful to display the images with the same window width and level settings as used for their filming. If necessary, make further adjustments to the film printer to match the patient films to the monitor appearance, using the manufacturer's recommended procedures.

12. Repeat steps 6 through 8 until a film printer adjustment is found such that the filmed SMPTE pattern images and filmed patient images are a good match to their appearance on the monitor. Save the final films for future reference when troubleshooting film quality problems.

13. Using a film densitometer, measure the optical density of the 0, 10%, 40%, and 90% gray-level patches of the SMPTE pattern. Do this for the image in the upper-left frame of the film, the upper-right of the film, and the lower-right of the film. Note any significant variations from one location to another.

    Record the measured optical density values on a new copy of the Film Printer Control Chart. This will be the new chart for the weekly film QC measurements (MRI Technologist's Section, Appendix VIII.C).

ADDITIONAL BASELINE DATA

At this point, the baseline data for the weekly film printer QC measurements have been acquired. The remaining three steps gather some additional data, which are easy to obtain and are valuable when troubleshooting filming problems.

1. Film printers can print test patterns that are generated internally by the printer. If it is available, print an internally generated SMPTE pattern; otherwise, print an internally generated gray-level step pattern having at least eight steps. Consult the manufacturer's documentation or the service engineer for the correct way to do this.

2. Using a film densitometer, measure the optical densities of the 0, 10%, 40%, and 90% gray-level patches of the internally generated SMPTE pattern.

3. If a gray-level step pattern was used instead of the SMPTE pattern, find and measure the steps with optical densities closest to 2.45, 2.10, 1.15, and 0.30.

4. On a separate page for inclusion in the film printer QC section of the QC notebook, do the following:

    a. Record the measured optical densities for the internally generated test pattern.

    b. Note which internally generated pattern was used and how it was printed.

c. If a step pattern was used instead of the SMPTE pattern, note which steps of the pattern were used for the optical density measurements.

d. Put marks on the film indicating which patches or steps were measured. Save the film for future reference.

CORRECTIVE ACTION

When the qualified medical physicist/MRI scientist is called in to assess problems with camera performance, the following steps should be followed:

1. Determine whether the problem lies in the camera and/or processor or if it lies in the part of the film system chain between the scanner and the camera.

   Perform steps 1 and 2 listed under additional baseline data; that is, print the internally generated test pattern from the film printer and measure the optical densities. Compare these measurements with the baseline measurements previously recorded. Use the same optical density ranges for the control limits on this data as are used for the corresponding optical density values in the weekly QC.

   If the optical densities are outside the control limits, there is a problem with the processor or the camera. If the optical densities are within control limits, the problem lies in the part of the film chain from the scanner to the interface electronics in the camera.

2. If the problem is determined to lay in the camera or processor:

   a. If the system has a wet-process film processor, contact the service engineer responsible for the processor. In systems with a wet-process processor, it is the component most often responsible for film quality problems.

   b. If the system has a dry process camera, or it has a wet-process processor that has been checked and found to be functioning correctly, contact the service engineer responsible for the camera.

3. If the problem is determined to lay in the part of the film chain between the scanner and the film printer interface electronics:

   Notify the service engineers responsible for the components of this part of the film chain and require them to cooperate in identifying and correcting the problem. Normally this will include the film printer service engineer and the scanner service engineer. If there is a PACS or digital imaging network between the scanner and the camera, the service engineer for that system must be involved as well.

There is, in general, no easy way to further localize the cause of the problem. Therefore, it is important to insist that the engineers responsible for the various components of this part of the film chain work cooperatively to resolve the problem. The QC data and data from step 1 above should be shown to the engineers so they have a clear understanding of the nature of the problem and the reasoning that led to identifying the problem within this part of the film chain.