QUALITY ASSURANCE TESTING EVALUATION AND COMPARISON FOR MAGNETIC RESONANCE SIMULATOR AND NON-SIMULATOR MAGNETIC RESONANCE IMAGING MODALITIES

By

Jacob Saverio Buatti

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ABSTRACT

Introduction

Magnetic Resonance (MR) Imaging is imperative to radiation therapy (RT) treatment planning and is used to delineate tumor volumes and normal tissue structures. MR images are susceptible to many sources of significant geometric uncertainties that reduce the geometric fidelity of the image ultimately limiting its application in radiation medicine. The Magnetic Resonance Simulator (MR-SIM) has been shown to reduce setup related uncertainties and is approved for MR-only treatment planning in specific anatomical sites.[48] Stricter Quality Assurance (QA) testing regimens and tolerance for an MR-SIM have recently been published by the American Association of Physicists in Medicine (AAPM) Task Group (TG) 284. Altered QA testing for an MR-SIM, as suggested by TG-284, has not been compared to that performed for a standard diagnostic MR system.

Methods

Quality Assurance tests, the recommended or required frequency of performing tests, and the performance tolerances/action criteria were evaluated for an MR-SIM system and a standard diagnostic MR system. Major QA documents and guides, TG-284 and American College of Radiology (ACR) MR Quality Control (QC) Manual, were compared for the MR-SIM and standard MR system, respectively.

Annual MR QA tests from a standard MR system accredited by the ACR were performed. Stricter recommended tolerances from TG-284 were used to evaluate the measurements from the standard MR system to see if the standard MR system would meet RT-specific performance requirements.

Results

Five new tests were included in TG-284 and were specific to an MR-SIM system equipped with an external laser positioning system. Six of the tests described by the ACR were excluded from MR-SIM testing. Four QA tests of similar system performance characteristics had stricter tolerances for an MR-SIM system. One similar test could not be evaluated and required MR system manufacturer tolerance levels.

The four QA tests that had stricter tolerances for an MR-SIM were chosen for measurement. Data from annual QA testing of a commercial MR scanner were acquired for transmitter gain, magnetic field homogeneity, low-contrast detectability (LCD), and table motion accuracy. All tests performed from ACR testing were within tolerances specified by the ACR. LCD measurements failed the 40-spoke minimum tolerance from TG-284 (≥3.0T), where 40 and 38 total LCD spokes were counted for T1 and T2 weighted images, respectively. Transmitter gain was determined to be 5.04% greater than the baseline transmitter gain value, which was outside the 5% tolerance of TG-284. Table motion accuracy measurements were within both ARC and TG-284 tolerances, and magnetic field homogeneity could not be directly evaluated because of phantom size differences.

Conclusion

QA testing differences from the ACR's standard MR system QA guide[13] and from the TG-284 MR-SIM QA testing guide were identified. The evaluation of TG-284 and ACR testing guidelines clarified system performance differences between a standard diagnostic MR and MR-SIM system. Both systems were found to have many similar QA testing procedures, with only four tests having altered recommended tolerances, six ACR

tests excluded from TG-284, and five additional tests for an MR-SIM system. Altered tolerances should be followed for an MR-SIM system to ensure greater performance for RT simulation studies. The six tests excluded from TG-284, but included in the ACR MR QC Manual, should be performed as routing QA tests for an MR-SIM system to promote the safe operation of the system, proper viewing of images, and sufficient image quality characteristics. Furthermore, should ACR accreditation be sought for an MR-SIM system, MR-SIM specific tests and tolerances should be prioritized over standard MR system QA.

1. INTRODUCTION

In radiation oncology, magnetic resonance (MR) images are used to diagnose disease, plan radiation therapy (RT) treatment, guide radiation (in MRI-Guided RT), and/or to assess tumor response to radiation.[7] In comparison to X-ray computed tomography (CT) images, MR offers superior soft tissue contrast that provides enhanced details of internal structures, which ultimately improves the physicians' ability to delineate targets or volumes to avoid within the body, such as tumors or radiosensitive normal tissues. Mounting evidence for MRI in the treatment planning process suggests that MRI may reduce treatment-related toxicities via improved target localization and can be used to visualize areas of high tumor burden which may be specifically targeted with escalated dose.[8 12]

Although these benefits exist, CT largely remains the primary image modality used for radiation treatment planning over MR.[18] This is due to CT images containing electron density information necessary for accurate dosimetric calculation in homogeneous tissues and because CT images have minimal to no localization uncertainties.[12] Conversely, MR images have decreased spatial fidelity. Inherent geometric uncertainties in MR from gradient nonlinearities, inhomogeneous static magnetic fields, magnetic susceptibility of the subject, and user error create small differences in MR signals that manifest as spatial offsets.[1 6 7 8 11 12] Geometric distortions caused by these sources can be as great as 2 mm in certain regions of anatomy.[4] These uncertainties pose challenges to using MR for treatment planning, where extremely high doses of radiation are prescribed to regions with extreme accuracy.[5] For example, a geometric accuracy of ≤ 2 mm for most RT application and ≤ 1 mm for stereotactic radiosurgery have been suggested.[7 10] Therefore, CT images are

inherently the superior representation of where targets and at-risk organs are located within the patient.

Currently, CT images and multiple sets of MR images are used for treatment planning purposes. While CT images remain the image set used for reference geometry, MR images are co-registered with CT images such that the delineation of targets and OARs is performed using both CT and MR images. This system utilizes the superior soft tissue characteristics of MR images and maintains the geometric fidelity from CT.

This workflow is commonly used in radiation oncology departments, including at the Oregon Health and Science University (OHSU). While other departments may have different workflows or a dedicated MR-SIM system, the acquisition of MR images outside of a simulation setting can introduce significant uncertainty. CT images are acquired with treatment simulation protocols where the patient is positioned in the same setup for treatment. This process utilizes RT-specific equipment including a flat table top, external laser positioning systems (ELPS), and immobilization devices which increase the reproducibility of the patient's position and state of interest (i.e. breath holds) between simulation and treatment. Conversely, the MR images are not acquired using the same equipment. Uncertainty in anatomical position can be increased due to slight differences in patient positioning and setup. The co-registration of CT images with MR images have shown shifts as great as 2 mm in the brain and 5 mm in the abdomen are possible without the use of simulation accessories.[8]

The increased use of MRI in medicine over the past decade has led to significant improvements in MR technology and an increase in its applications. Already, MR images are necessary for treatment planning purposes solely due to their superior soft tissue

contrast. However, uncertainties created from geometric distortions, lack of electron density information, and lack of immobilization device compatible MR equipment had previously limited its adaptation to the treatment simulation setting.[8] Now, advancements in MR imaging technology, pulse sequences, and geometric distortion correction algorithms have improved the localization capabilities, scan times, and overall capabilities of MR modalities. Additionally, innovations in computer learning and algorithms have supported the development of software with the capability to synthesize CT data from MR images. As of now, three synthetic CT applications exists with limited FDA approval for use in specific regions of anatomy.[8] These solutions to using MR for treatment planning have led to creation of an MRI 'Simulator' system as well as the MRI Linac.

The MR simulator, or MR-SIM, is an imaging modality equipped with the standard devices and design requirements necessary for acquiring images that meet the requirements for radiation oncology treatment planning purposes. Specifically, the MR-SIM system includes an ELPS, a flat tabletop, MR-compatible immobilization devices, and radiofrequency (RF) coils that can accommodate immobilization devices and RT accessories.

To ensure that MR systems are functioning properly and that MR images meet the requirements of RT treatment planning, an RT-specific assessment of MR system function and image quality must be performed. On January 1st, 2021, the American Association of Physicists in Medicine (AAPM) Task Group 284 released a report outlining the requirements and recommendations for quality assurance and implementation of an MR-SIM to radiation oncology departments.[8] This report includes siting and design requirements, staffing requirements, safety considerations, room design specifications,

quality assurance recommendations, workflow designs, and more. As MR imaging improves, the installation of MR simulators and MR-Only treatment planning is expected to increase.

Diagnostic MR images are utilized for treatment planning in many sites, such as OHSU. However, until the publication of TG-284, MR QA tests that meet the needs for RT treatment planning and simulation had not previously been addressed.[7] An investigation into the differences between QA tests recommended for an MR-SIM system and QA tests already performed for a standard MR system is yet to be done at OHSU.

This work identifies the differences and similarities of MR system quality assurance testing programs for diagnostic MRI systems and MR-SIM systems. The purpose is to compare testing recommendations for RT-specific units discussed in TG-284 to what is already being performed on the standard diagnostic MR system that is accredited by the American College of Radiology MR Accreditation Program.

2. BACKGROUND

2.1 X-RAY COMPUTED TOMOGRAPHY

X-ray computed tomography is a medical imaging tool that uses X-ray radiation to create images of patient anatomy for the purpose of diagnosing patient diseases, visualizing injuries, and treatment planning for radiotherapy. Like a radiograph, CTs use X-rays to form images. However, CT is unique in that the x-ray source rotates around the patient at incredibly fast rates creating thousands of two-dimensional radiographs every rotation.[6] While the x-ray tube spins around the patient the patient is moved at a constant rate (helical acquisition) or incrementally (axial acquisition) through the bore of the machine to obtain data in different regions of the body.

As X-rays pass through patient anatomy they are scattered, absorbed, or attenuated through Compton scattering interactions and/or photoelectric absorption. The amount of radiation that is attenuated or absorbed by the patient is dependent on the electron density of the tissues and the thickness of material that the radiation must cross through before reaching the detector. More dense materials such as bone absorb significantly more radiation than other tissues. Conversely, soft tissues attenuate less of the photon spectrum. Using advanced projection mathematics and algorithms, the millions of data points collected are reconstructed to produce the three-dimensional volumetric data. The values of each voxel measured represent the attenuation coefficients of the tissues and are called Hounsfield Units (HU). HU's are displayed in grayscale, where water is always 0 HU and air is -1000 HU.[6]

At energies used for CT, (120-140 kVp), the difference in the attenuation coefficients and HUs of soft tissues is relatively small in comparison to the difference between bone and soft tissue.[6] The ability to obtain high contrast for soft tissues with similar electron densities is therefore not achievable. As a result, the visualization of anatomy for the purpose of treatment planning is not ideal.

2.2 MAGNETIC RESONANCE IMAGING

A magnetic resonance imaging modality is a medical imaging device that exploits the natural magnetization of hydrogen protons, ^{1}H, primarily found in water molecules (H_2O) of a patient to obtain information about the internal structure and function of anatomy. The physical principal underlying MR image acquisition is known as the nuclear magnetic resonance (NMR) phenomenon, which describes the natural magnetization of nuclear elements. It is known that atoms are composed of elementary particles; electrons,

protons, and neutrons. Of which, the electron has a negative charge equal to -1.602 x 10^{-19} Coulombs, the proton has a positive charge equal to +1.602 x 10^{-19} Coulombs (C), and the neutron has no charge.

From quantum mechanics, it is known that these elementary particles also have a characteristic spin, or angular momentum. Because protons have both a charge and a spin, a magnetic dipole moment occurs about the spin axis of the proton. In the absence of a magnetic field, the magnetic dipole moments of protons in tissues are randomly oriented. By using a large static magnetic field, typically 1.5 T or 3.0 T clinically, produced by a superconducting magnet, one can force the magnetic dipole moments of the protons to align parallel or anti-parallel to the static field. The protons are then considered to be in equilibrium with the magnetic field and the bulk magnetization is in the same direction as the static magnetic field.

The spinning motion of the protons does not allow the alignment of the magnetic dipole moment to be stable with the magnetic field and instead, the protons precess about the static magnetic field at a known frequency, ω_0, known as the Larmor Frequency. This frequency is dependent on the strength of the static magnetic field, B_0, and the gyromagnetic ratio, Γ, which is characteristic of the specific molecules or atoms of the tissue (Equation 1). For hydrogen protons in water, where the gyromagnetic ratio is 42.58 MHz/T, the Larmor Frequency in a 1.5 T static field would be 63.87 MHz.

$$\omega_0 = \Gamma B_0 \quad (1)$$

The vector sum of all the magnetic dipole moments of protons precessing about an axis in space, called the bulk magnetization, M_{xyz}, is small compared to the static magnetic field and cannot be measured. Additionally, the precession of the protons is not synchronized

and therefore no frequency information can be measured. To obtain a measurable signal, a radiofrequency (RF) pulse is used to excite the protons and misalign the direction of the magnetic dipole moment to 90° or 180° to the direction of the static magnetic field. The bulk magnetization, M_{xyz}, of the protons is then perpendicular or opposite to the direction to the static magnetic field (M_x or M_y at 90° or $-M_z$ at 180°). Additionally, the RF pulse synchronizes the precession of protons so that they precess in unity, or "in phase." To achieve this, the RF pulse must have the same frequency as the Larmor Frequency, ω_0, of the precessing protons in the static magnetic field.

When the RF pulse is turned off, the protons de-phase and return to equilibrium with the static magnetic field, B_0 . The return of protons back to equilibrium conditions results in measurable energy emissions that are proportional to the number of excited protons in the volume. This energy is measured by RF receiver coils and comprises the information needed for MR image formation.

The rate at which dephasing occurs is known as the free induction decay (FID) and is caused by micromagnetic inhomogeneities in the sample that naturally cause dephasing. The frequency of precession, ω_0, manifests as a measurable sinusoidal electronic signal. As dephasing increases, the signal becomes dampened and eventually dissipates. Images using the signals from dephasing are classified as T2-weighted images. The rate at which a sample de-phases is characteristic of proton density, molecular structure, and therefore tissue composition.

Similarly, the rate at which de-excitation occurs can also be measured. T1 relaxation, or spin-lattice relaxation, is the term that describes the rate at which protons excited by an RF pulse return into equilibrium with the static magnetic field. In particular,

the rate at which de-excitation occurs depends on the molecular arrangement and the structure of the hydration layer, which are characteristic of different tissues.

Both T1 and T2 weighted images are used in radiation oncology to identify specific characteristics of human anatomy. In some instance, T1-weighted, FLAIR, or T2-weighted MR images may be preferred for delineating specific structures.

2.2.1 OPTIMIZED PULSE SEQUENCES

Image data in MRI is acquired primarily with three major pulse sequences: spin echo (SE), inversion recovery (IR), or gradient echo (GE).[6] In radiation oncology, most pulse sequences used are SE sequences.[8]

A spin echo pulse sequence is a series of two RF excitation pulses that produce FID of a particular tissue. Specifically, a 90-degree RF pulse is followed by a 180-degree RF excitation pulse at TE/2. The purpose of using dual 90-degree and 180-degree RF pulse is to re-phase the system by the end of TE. The second, 180-degree, excitation pulse undoes natural dephasing from magnetic field inhomogeneities. This works at 180 degrees because the magnetic field is oriented opposite to the static field. Thus, phase differences caused by inhomogeneities are undone and reverted once excited to 180 degrees. SE sequences are used in radiation oncology and are suggested for treatment planning because the 180-degree RF pulse corrects B_0 homogeneities and reduces geometric uncertainties from the magnet.[8]

2.3 SPATIAL DISTORTIONS

A major reason why MR-only treatment planning had not been possible was due to susceptibility of MR images to significant spatial errors.[7 8 16] These errors, called spatial distortions, are caused by variations in the local magnetic field and are caused by the MR system or the subject being imaged. The sources of these errors come from small inhomogeneities in the static magnetic field, gradient nonlinearities, and variation in tissue composition.[4 6 7 8]

2.3.1 SPATIAL ENCODING IN MRI

Spatial encoding in MR imaging is achieved using a series of three gradient magnetic fields and tuned RF frequency pulses. These gradients alter the strength of the magnetic fields in all three spatial axis (x, y, z) which determine the anatomical region sampled, the processional frequencies of excited protons, and the phase of the hydrogen protons.

First, the slice selection gradient is applied. By producing a gradient magnetic field in the z-direction, protons at different positions precess at different frequencies as per the Larmor equation (Equation 1). Slice selection is achieved by using a specific RF pulse of finite bandwidth, $\Delta\omega$, that matches the precessional frequency of protons in a selected region. The strength of the gradient (mT/m) and the RF bandwidth affect the slice thickness by restricting the region in which precession is similar to the RF pulse. Steeper gradients will have thinner slices and low gradients will have larger slice thicknesses.

The next step in localization is application of the phase encoding gradient (PEG), which selectively excited protons along a second axis (x or y) by altering the phase of precessing hydrogen. A short-timed gradient is applied across the axial slice to briefly alter the precessional frequencies of protons based on the altered magnetic field. When PEG is

turned off, the precession returns to a uniform frequency, but the phases of the protons are altered. The phase information is eventually put into a matrix known as K-space and later used to create an image.

The final step of spatial localization uses a frequency encoding gradient (FEG) during echo collection, where another gradient is created on the third and last direction of the axial slice (x or y direction) to alter the precessional frequency of the protons within the slice. Protons in regions of higher magnetic field strengths will precess at a higher frequency than those in lower field (Equation 1). When the slice selection gradient and RF pulse are turned off and the frequency encoding gradient is turned on, the rate of deexcitation of protons as they return to equilibrium are altered. The received signals are then separated into different Larmor frequencies using the Fourier Transform and are related to their location relative the magnetic field strength created by the gradient. The information is then digitized and put into a matrix called K-space. Following image acquisition, the frequency information in K-space can be converted into image space using a reverse Fourier Transform.

2.3.2 DISTORTIONS FROM MAGNETIC FIELD INHOMOGENEITIES

2.3.2.1 STATIC FIELD AND GRADIENT FIELD DISTORTIONS

Localization of tissue signals in MRI heavily depend on the uniformity and strength of the magnetic field and the linearity of gradient fields. Inhomogeneities in the static magnetic field and gradient fields alter the precessional frequency and phase of protons, consequently altering the characteristics used in spatial encoding. These differences then result in spatial offsets. For example, if the gradient field is nonlinear, the frequency or

phase information is altered resulting in an image that incorrectly compresses or expands anatomy (Figure 1).

The static magnetic field and localization gradients typically contain inhomogeneities or are nonlinear, respectively. To reduce the effect of these differences, the static magnetic field should be tuned as best as possible during commissioning. For gradient nonlinearities, vendors have implemented corrections that minimize the effects of nonlinearities.[8 16] Gradient corrections can be turned on or off and must be turned on for RT treatment planning.

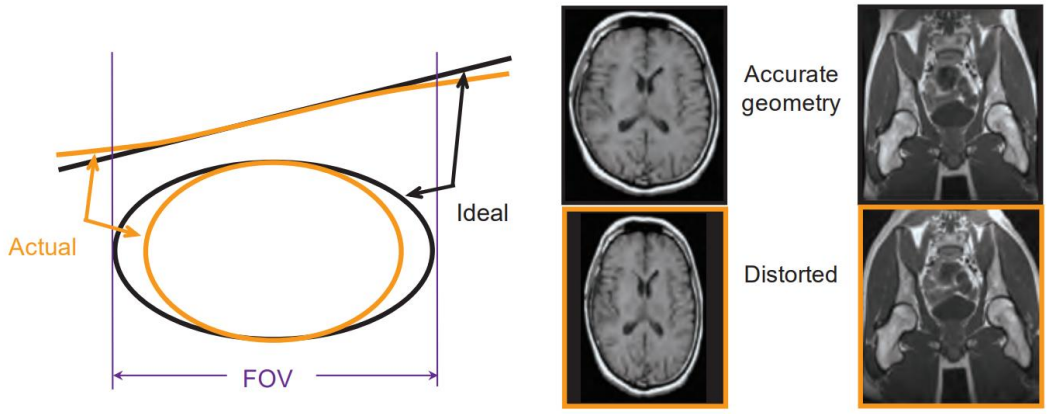

Figure 1. Bushberg et al. Figure 13-25. Nonlinear gradient magnetic fields (left) alter the phase and precessional frequency of protons which manifests as geometric distortion in the reconstructed MR image. Reprinted from *The Essential Physics of Medical Imaging* with permission for Dissertation/Thesis.

2.3.2.2 CHEMICAL SHIFT DISTORTIONS

Another source of spatial errors from MRI includes the Chemical Shift artifact. The measured MR signals used for image reconstruction are all assumed to be from H^1 protons from water, which have gyromagnetic ratio of 42.58 MHz/T and therefore an assumed Larmor frequency determined by the strength of the magnetic field. However, not all protons precess at the same frequency. Natural differences in the molecular structures of tissue, such as fat, create intrinsic differences in the micromagnetic environment. This

difference causes protons to precess at a lower frequency of approximately 3.5 parts per million (ppm).[6] Even though this difference is small, the shift in location is as large as 0.5 mm to 1 mm (Figure 2).[16] For radiation oncology purposes, large chemical shift artifacts are undesirable. Optimized sequences can be used to reduce the shift artifact but reduced the signal to noise ratio.[16]

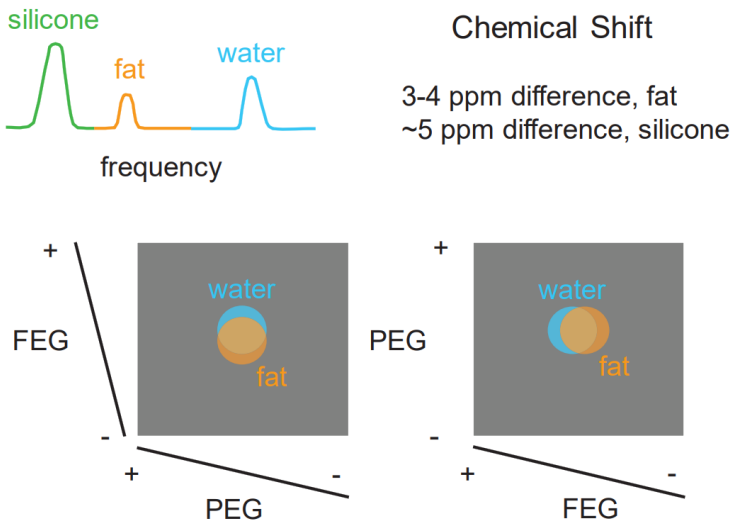

Figure 2. Bushberg et al. Figure 13-31. Depiction of a chemical shift artifact showing small shifts of fat tissue due to natural precessional differences of the tissue. Reprinted from *The Essential Physics of Medical Imaging* with blanket permission for Dissertation/Thesis.

2.3.2.3 SUBJECT-INDUCED SUSCEPTIBILITY

The last source of spatial distortion in MR imaging comes from the patient, or 'subject'. Ferromagnetic, diamagnetic, or paramagnetic materials alter the local strength of the static magnetic field near the nucleus of the atom.[6] This causes slight variations in field strength and compromises the geometric fidelity of the image. These distortions cannot be removed from the reconstructed image.

A study that simulated magnetic field inhomogeneity maps in software for 19 images of the brain has shown that 86.9% of brain anatomy had shifted less than 0.5 mm, 97.4% had shifted less than 1 mm, and 99.9% of brain tissue had shifted less than 2 mm in these images.[4] It was found that regions where drastic tissue interfaces occurred, such as from brain to adjacent air cavities, had the greatest estimated distortions.[4]

2.3.3 IMAGE REGISRATION AND FUSION

Image registration and fusion are mathematical transformation tools used to combine data from multiple image sets. Image registration determines the mathematical transformation to align two image sets in a shared coordinate system. Using registration data, the two image sets can be combined, called image fusion. Image fusion joins the image data from two sets using the image registration information and displays both sets such that similar anatomical points are overlayed on top of one another.

The purpose of image registration is to combine information from multiple image sets and can be used for assessing tumor response, tissue delineation, and/or for adaptive treatment planning.[5] In radiation therapy, image registration and fusion has been used to aide in defining patient anatomy. T1 and T2 images, which are valuable for observing soft tissues in patients, are registered to the CT images acquired during simulation. Because CT images for treatment planning are acquired with simulation protocols and are not susceptible to geometric distortion, the location of anatomy on CT images is considered the most accurate representation of patient anatomy in space. In other words, CT images are used as spatial reference geometry for all treatment planning.

When registering MR and CT images, finding similar anatomical points and validating the image registration is a challenge.[16] Typically, image registration accuracy

for most clinical purposes must be accurate to about 2 mm and requires additional quality assurance testing and equipment to validate.[5] To improve registration accuracy, identical setups can be used for both image acquisitions.[16] Alternatively, MR-only treatment planning could be used.

2.4 MR SIMULATION

A magnetic resonance simulator, or MR-SIM, is a solution to reduce uncertainties from setup differences and image registration or fusion that led to spatial offsets and potential geographical misses in radiation delivery. Much like the CT-SIM which has been used heavily for the last 10-15 years, the MR-SIM acquires images that meet the requirements of radiation treatment planning. This includes high spatial fidelity, a large field of view, high spatial resolution, patient in treatment position, equipment, state of interest (i.e. breath hold), and optimized imaging sequences.

Images acquired with MR-SIM must have high spatial fidelity. Optimized MR sequences, distortion mitigation, and correction algorithms are used to ensure that the images used for treatment planning are spatially precise.[8] A large field of view ensures that immobilization devices and all necessary patient anatomy are included in the image and eventual dosimetric calculations.[18] High spatial resolution is necessary for observing small details in patient anatomy including fine tumor details that enable superior target contouring. States of interest and patient positioning are used to optimize normal tissue sparing and anatomical stability.

2.5 QAULITY ASSURANCE OF MR AND MR SIMULATORS

Quality assurance tests are performed for MR systems to ensure that the system is operating safely, performance is not drifting far from the baseline set during

commissioning, and that the image integrity meets standards suggested by agencies such as the ACR and AAPM. Routine QA testing performed daily, weekly, monthly, quarterly, and annually have been recommended to assess the function of MR units used for clinical purposes. QA tests encompass a wide range of assessments including general system checks, image quality tests, system safety tests, general safety checks, patient monitoring system checks, emergency system checks, and more. Performance standards defined by the ACR and AAPM ensure that the system can produce high quality images that can be used by physicians in many fields such as radiology or radiation oncology. However, the original documents defining the requirements of MR systems are outdated and/or do not specifically address the concerns for radiotherapy treatment planning.[8 12]

The most recent AAPM publication describing recommendations and requirements for MR QA assessment is the AAPM report 100, "Acceptance Testing and Quality Assurance Procedures for Magnetic Resonance Imaging Facilities," published over a decade ago, in December 2010. This report details strategies and procedures for an MR QA program. However, this document does not suggest the frequency of QA tests and has not been updated to reflect innovations in MR technology or new applications, such as MR-only treatment planning.[9]

More recently, in 2015, the ACR published the *Magnetic Resonance Imaging Quality Control Manual*.[13] The purpose of this report was to suggest a minimum level of performance for an MR scanner and outline staffing and safety requirements. If the MR scanner meets the minimal level of performance and the operating institution meets testing, safety, and operational standards, then they may become accredited by the ACR.

Accredited systems are then said to be properly functioning and operated by well-trained personnel.

Part of the ACR accreditation program includes routine quality assurance tests that are performed by MR Technologists and Medical Physicists. To standardize the evaluation of MR system performance across institutions, the ACR has developed two phantoms, the ACR Large MR Phantom and ACR Small MR Phantom, that can be used to test seven image quality metrics: geometric accuracy, high-contrast spatial resolution, slice thickness accuracy, slice position accuracy, image intensity uniformity, percent-signal ghosting, and low-contrast object detectability. Furthermore, the ACR has also defined T1-weighted and T2-weighted imaging sequences to be used for image evaluation in addition to the institution's frequently used T1 and T2 weighted sequences.

The ACR QC manual also includes basic system checks that ensures the MR system is working properly. A visual checklist has been developed by the ACR for MR Technologists to perform weekly and for the Medical Physicist to review or evaluate annually. The visual checklist consists of simple tests which check the functionality and presence of miscellaneous systems or items including the patient transport and gantry system, laser film function (if applicable), RF integrity of the room, control room systems, and facility safety indicators and equipment (Table 1). Following the completion and evaluation MR system QA tests by the Medical Physicist, the acquired images and a report of the results are sent to the ACR for review.

Table 1: The ACR's Visual Checklist

	Visual Checklist Items	Evaluation
1.	**Patient Transport and Gantry**	
	Table position and other displays	Pass/Fail
	Alignment lights	Pass/Fail
	Horizontal table motion and stability	Pass/Fail
	Vertical table motion and stability	Pass/Fail
2.	**Filming Viewing**	
	Laser camera	Pass/Fail
	Light boxes	Pass/Fail
3.	**RF Integrity and Control Room**	
	RF door contact	Pass/Fail
	RF window-screen integrity	Pass/Fail
	Operator console switches and lights	Pass/Fail
	Patient monitors	Pass/Fail
	Patient intercom	Pass/Fail
	Room temperature and humidity	Pass/Fail
4.	**Facility Safety**	
	Emergency Cart	Pass/Fail
	Safety warning signage	Pass/Fail
	Door indicator switch	Pass/Fail
	Cryogen level indicator	Pass/Fail
	Oxygen monitor	Pass/Fail

The ACR QC Manual briefly acknowledge radiation oncology imaging needs but suggest that the radiation oncology medical physicist should review MR system performance and recommend different and possibly stricter action criteria, or tolerances, for tests if needed.[9 13] Additionally, QA tests and tolerances are not specific to an MR-SIM system, which has distinct and unfamiliar equipment to standard MR systems.

The APPM Task Group 284 Report: *Magnetic Resonance Imaging Simulation in Radiotherapy: Considerations for Clinical Implementation, Optimization, and Quality Assurance* (TG-284) interprets the MR imaging needs of Radiation Oncology departments and, specifically of RT-specific MR modalities like MR-SIM systems. TG-284 describes

the requirements and considerations for machine selection, implementation, equipment, staffing requirements, safety program requirements, QA testing procedures and more.

QA tests recommended by TG-284 are based off QA testing regimens created by the ACR for standard MR systems. In fact, the ACR Quality Control Manual (ACR, Reston, VA)[13] is frequently referred to throughout TG-284. Additionally, the use of the ACR MR Phantoms is suggested for QA testing of MR-SIM systems. For institutions where cross-disciplinary Medical Physics expertise exists in Diagnostic Radiology and Radiation Therapy, the differences and similarities in MR QA testing procedures and their respective tolerances is not clear or obvious.

This work investigates the differences and similarities between QA testing regimens and tolerances between the standard MR systems and MR-SIM systems. The goal is to determine what changes must be made to current MR testing procedures to fit with new recommendations for MR-SIM systems and radiation oncology specifications.

2.5.1 SELECTED QA TEST DESCRIPTIONS

For this work, not all tests are described. For details regarding QA test descriptions, the reader should refer to the ACR QC Manual[13], TG-284[8], or other resources. Low-contrast detectability, table motion smoothness and accuracy, and transmitter gain are described because testing tolerances were found to be different between the ACR QC Manual and TG-284 (See Section 4.1.3).

2.5.1.1 LOW-CONTRAST DETECTABILITY

Low-contrast object detectability assesses the ability of the MR system to distinguish objects of low contrast. For these tests, objects of decreasing contrast are viewed to determine the extent to which the MR system can reconstruct images that have

similar proton densities or similar tissue characteristics. This test is meant to check that the system can appropriately distinguish different tissues and that the acquired images can be used for clinical purposes such as diagnosing disease or defining tumor volumes.

2.5.1.2 TABLE MOTION ACCURACY

Table motion and smooth accuracy QA tests characterize that accuracy and ability of the table to translate smoothly across the clinical range. Namely, the motion of the table from outside the bore to the imaging isocenter and center of the MR bore. The importance of precise accurate table motion is to improve the localization accuracy of the imaging acquisition.

2.5.1.3 TRANSMITTER GAIN

Transmitter gain measurements test the performance of the RF frequency pulses used for image sequences. Transmitter gain is required to properly calibrate RF flip angles used in pulse sequences. Poorly calibrated gain may alter the flip angle and the resulting image contrast. These effects are more apparent with stronger fields such as a 3 T magnet

3. METHODS

An evaluation of quality assurance (QA) tests for a hypothetical MR-SIM system was done. QA tests, their respective tolerances, and suggested testing frequencies for an MR-SIM had recently been outlined by the AAPM Task Group Report No. 284.[8] The testing recommendations from this report were compared to QA recommendations for a standard MR system. The ACR's MR QC Manual and its recommended and required MR QA assessments were used as the standard QA testing protocol and timeline for standard MR systems. Each report and its QA testing procedures were directly compared to identify

differences and similarities between the extent of QA tests, testing frequencies, and passing tolerances/action criteria.

To further understand testing similarities and differences, annual and weekly QA reports for a standard MR system were evaluated. For tests whose tolerances differed in TG-284[8] and ACR QC Manual[13], the data from the standard MR was assessed using both TG-284 tolerances and ACR tolerances to determine if standard MR performance was appropriate for simulation and RT purposes.

3.1 QUALITY ASSURANCE TESTING EVALUATION

Quality assurance tests for an MR-SIM system, described in TG-284, were outlined. A list of all tests, the testing frequency, and the tolerances for each QA test was created. Similarly, a list of QA tests, frequencies, and tolerances for standard MR systems from the ACR MR QC Manual was created. Tests whose procedures evaluated the same system characteristics and used identical testing procedures were identified. Identical tests were then compared using the noted frequency of testing and the minimum performance tolerances set for each test. In instances where recommended action criteria or tolerances were not specified by the ACR, the tolerances for a Philips Ingenia 3.0T MR system (SN 71556, Philips Medical Systems, Cleveland, OH) at OHSU were substituted for comparison to MR-SIM recommended tolerances. QA tests that were not included in both reports or had altered testing procedures were recognized. The relevance of these dissimilar tests with respect to the two systems were assessed to determine specificity to the MR-SIM system.

3.2 EQUIPMENT

An MR-SIM system did not exist at OHSU at the time of this review. Thus, MR-SIM specific tests could not be performed. Instead, annual and weekly QA reports for a Philips Ingenia 3.0T MR system accredited by the ACR MRI Accreditation Program were obtained from the Diagnostic Radiology Department at OHSU. Major equipment difference between the Philips MR system and the hypothetical MR-SIM included a rounded tabletop, small bore, no external laser position system, and RF coils that were not tested for compatibility with immobilization devices.

Table 2. Annual and Weekly MR QA tests and Equipment for ACR MR Accreditation Program

QA Tests Performed	Equipment
Annual Tests	
1. **ACR Phantom Tests**	
Setup and Table Position Accuracy	ACR MR Phantom
Geometric Accuracy	ACR MR Phantom
High-contrast spatial resolution	ACR MR Phantom
Slice position accuracy	ACR MR Phantom
Image intensity uniformity	ACR MR Phantom
Percent Signal Ghosting	ACR MR Phantom
Low contrast object detectability	ACR MR Phantom
Artifact evaluation	ACR MR Phantom
2. **Magnetic field homogeneity**	Uniform Spherical Phantom
3. **Monitor performance**	
Visual Analysis	SMPTE Pattern
Photometric Analysis	Luminance Meter
4 **Laser Film QC**	NA
5. **Center Frequency and Transmitter Gain**	Automatic/System Software
6. **Visual Checklist**	Review
7. **Safety Program Assessment**	Review
8. **Weekly Technologists QC**	Review
9. **RF Coil Performance**	ACR MRI Phantom, varying sizes
Volume coil image uniformity	of water-filled phantoms[a], other
Volume coil ghosting ratio	
Surface coil signal-to-noise ratio	
Weekly ACR Tests	
1. **Transmit gain Central frequency***	
2. **Basic coil SNR check**	ACR MR Phantom
3. **Basic spatial fidelity check**	ACR MR Phantom
4. **High-contrast spatial resolution**	ACR MR Phantom
5. **Low-contrast detectability**	ACR MR Phantom
6. **Table Setup and Position Accuracy**	ACR MR Phantom
7. **Artifact evaluation**	ACR MR Phantom
8. **Visual checklist**	Review

[a]Water-filled phantoms for coils tests are given in the appendix (Table A19).

Annual testing included a total of nine types of tests on the MR unit, while the weekly QC tests included 8 total tests (Table 2). Annual and weekly QA tests were performed following ACR guidelines in the ACR QC Manual[13] and ACR Testing Guidance

for the Large ACR MR Phantom[2] including which imaging sequences were used, phantoms, equipment, testing procedures, and passing tolerances.

The Large ACR MRI Phantom (SN: J130151, American College of Radiology, Reston, VA) was used for parts of annual and weekly QA tests (Table 1, Figure 3). Specialized structures within the phantom were designed to test seven image quality metrics: geometric accuracy, high-contrast spatial resolution, slice position accuracy, percent intensity uniformity (PIU), percent signal ghosting (PSG), and low-contrast detectability. Refer to the ACR's Large MRI Phantom Testing Guidance document for details regarding phantom inserts and instructions on how to perform measurements and assessments.

Figure 3: Image of the ACR MR Phantom used for testing.

Phantoms of varying volumes and sizes were used to test RF coil performance characteristics including PIU, PSG, and SNR. Bottle phantoms with sizes of 2000 cm^3, 3000 cm^3, and 5000 cm^3 as well as small extremity, knee, foot, wrist, and shoulder bottle phantoms were used to determine SNR, PSG, and PIU for a total of eight volume coils and one surface coil. Further details regarding which phantom was used for each RF coil test are contained in the annual QA report (Appendix 8.1).

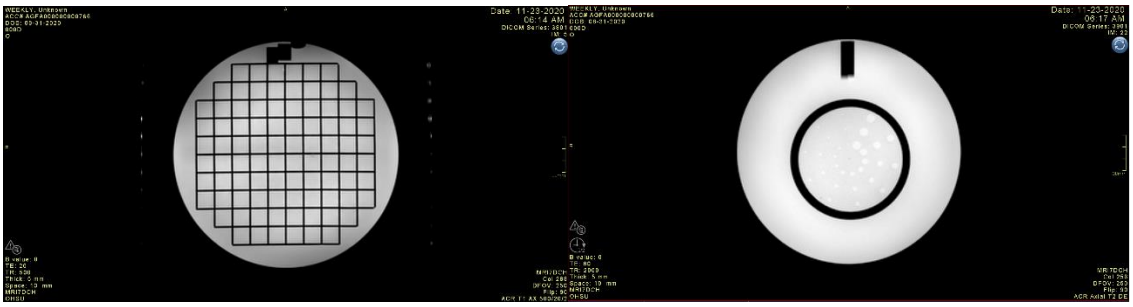

Figure 4: MR images of two ACR MR Phantom inserts used for assessing image quality metrics in routine QA tests. (A) Slice 5 of the Large ACR MR Phantom depicting a grid insert used for assessing geometric distortion and accuracy. (B) Slice 11 of the Large ACR MR Phantom depicting 10 "spokes" of low contrast objects used for assessing low-contrast object detectability

3.3 IMAGING SEQUENCES

Imaging sequences used for ACR annual and weekly testing included an axial T1-weighted and T2-weighted sequences defined by the ACR as well as T1-weighted and T2-weighted axial sequences typically used for brain scans at OHSU (Table 3). Details regarding required sequences for ACR testing guides can be found in the ACR QC Manual.

[2 3 13]

Table 3. MR Imaging Studies for ACR Annual Testing

Study	Pulse Sequence	TR[a] (ms)	TE[b] (ms)	FOV[c] (cm)	# of Slices	Slice Thickness	Slice Gap	NEX[d]	Matrix	BW[e]	Scan Time
ACR Sagittal Localizer	Spin Echo	200	20	25	1	20	NA	1	256x 256	55.8	0:53
ACR Axial T1	Spin Echo	500	20	25	11	5	5	1	256x 256	55.8	2:10
ACR Axial T2	Spin Echo	2000	20 80	25	11	5	5	1	256x 256	55.8	8:32
OHSU Axial T1 Brain Scan	Spin Echo	500	10	23	11	5	5	1	256x 190	49.8	0:59
OHSU Axial T2 Brain Scan	Fast Spin Echo	3000	80	23	11	5	5	1	420 x 288	113.7	0:39

[a]Repetition Time
[b]Echo Time
[c]Field of View
[d]Number of Excitations
[e]Bandwidth

3.4 TABLE POSITION ACCURACY MEASUREMENTS

Table position accuracy was measured using two methods. The first method was described in the ACR QC Manual[13] and determined the offset of the phantom as the table moved from the isocenter alignment lasers outside the bore to the isocenter of the MR scanner inside the bore. The Large ACR phantom was placed in a head coil on the table. Using the isocenter alignment lasers on the outside of the machine, the center of the grid structure within the ACR phantom was aligned with the lasers. Once aligned, an image of the phantom was acquired. Using the image viewing software, the distance was measured between the isocenter defined by the computer and the center of the grid structure initially aligned with the lasers outside the bore.

The second table motion test mirrored tests performed for CT-SIM machines. With the table outside of the MR bore, a marker was placed at a zeroed position using the alignment lasers on the system. To determine movement accuracy, the table was translated into the bore 150 mm and 300 mm.

The table motion controls on the outside of the machine could not be used for table motion testing. A distance indicator and digital display was not present on the unit. Instead, the translated distance was specified as a table shift in a survey sequence that had to be manually created. When the sequence began, the table automatically adjusted based on the shift specified in the survey sequence. Once the table had moved and the survey scan had completed, the distance from the stagnant isocenter lasers to the new position was measured using an MR safe ruler. The average distance between the two sets of measurements was recorded and checked to be within the tolerances specified by TG-284 and the ACR QC Manual.

3.5 VISUAL/OTHER QA TESTS

Items in the visual checklist, safety program review, and other miscellaneous tests were performed by audial inspection, visual inspection, or other appropriate means.

QA tests for ultrafast MR imaging, MR laser film, and soft-copy/monitor performance were either not performed or were performed in the annual assessment of the MR scanner, but are not in the scope of this report. All tests included in the comprehensive list of possible tests are in the appendix of this document (Appendix 8.1)

4. RESULTS

4.1 QA TESTING REVIEW

4.1.1 TESTING FREQUENCY

Review of all QA tests in TG-284 and the testing recommendations and requirements from the ACR's MR Accreditation Program was performed. TG-284 described a total of 28 tests (excluding film testing) be performed routinely by a Qualified Medical Physicist (QMP) or MR Technologist (MRT). The 28 tests included 8 daily tests, 16 monthly tests, and 4 annual tests (Table 4). Conversely, the ACR QC manual recommended a total of 26 tests be performed by the QMP or MRT, including 9 weekly tests, and 15 annual tests (Table 4).

Table 4: Number of daily, weekly, monthly, and annual QA tests for each system

Frequency	TG-284	ACR
Daily	8	NA
Weekly	NA	9
Monthly	16	NA
Annually	4	15
Total	**28**	**26**

4.1.1.1 ANNUAL QA TESTS (MR-SIM)

Three of the four of the annual MR-SIM QA tests were included in the scope of ACR MR QA testing with the same testing frequency (Table 5). The remaining test, 'determine or verify external laser offset from MR isocenter,' was included in TG-284, but not ACR guides. This test pertains specifically to an ELPS of an MR-SIM system.

Table 5A: Quality Assurance Testing Frequency Recommendations (For MR Technologists)

		Institution	
	QA Test	**TG-284**	**ACR**
	Technologist QC		
1	Functionality of patient communication and monitoring	D[a]	V[b]
2	Emergency cart or emergency couch release	D	V
3	Safety signage	D	V
4	Check bore for presence of foreign metal objects	D	V
5	External laser agreement with imaging plane	D	~[c]
6	Transmit gain Central frequency*	D	W
7	Basic coil SNR check	D	W
8	Basic spatial fidelity check	D	W
9	High-contrast spatial resolution	~	W
10	Low-contrast Detectability	~	W
11	Visual Checklist	~	W
12	Artifact Evaluation	~	W

[a]D – Daily

[b]V – Part of the visual checklist – recommended weekly.

[c]~ – Test not included OR repeated in another section.

Table 5B: Quality Assurance Testing Frequency Recommendations (For Medical Physicists or MR Scientists)

		Institution	
	QA Test	**TG-284**	**ACR**
	Medical Physicist or MR Scientist QA		
	Image Quality		
9	Geometric accuracy	M	A
10	High contrast spatial resolution	M	A
11	Low contrast detectability	M	A
12	Artifact evaluation	M	A
13	Percent image uniformity (PIU)	M	A
14	Percent signal ghosting	M	A
15	Central Frequency	M	A
16	Transmitter Gain	M	A
17	Flexible RF coil testing	M	A
	Mechanical Tests		
18	Table movement smoothness and accuracy	M	A
19	Laser alignment with imaging isocenter	M	~
20	Laser movement smoothness and accuracy	M	~
	Patient Marking		
21	Laser marking accuracy	M	~
	System		
22	Room temperature and humidity	M	V
23	Cold Head Operation	M	V
24	Cryogen level indicator	M	V
	Other		
25	Transmitter and Gain Calibration	A	A
26	Magnetic Field Homogeneity (B0)	A	A
27	Radiofrequency Coil Evaluation	A	A
28	Determine or verify external laser offset from MR isocenter	A	~
	Other		
29	Soft-Copy (Monitor) Control	~	A
30	MR Safety Program Assessment	~	A
31	Slice-Thickness	~	A
32	Slice-Position	~	A

[a]D – Daily

[b]V – Part of the visual checklist – recommended weekly.

[c]~ – Test not included OR repeated in another section.

4.1.1.2 MONTHLY QA TESTS (MR-SIM)

13 of the 16 monthly MR-SIM QA tests were included in some capacity of the ACR QC Manual but had varied testing frequencies (Table 5). The 13 of the MR-SIM monthly tests included were recommended to be performed less frequently, and on an annual basis, by the ACR. These tests included nine image quality tests, one mechanical test, and three system checks (Table 5B).

The remaining three of the 16 monthly MR-SIM QA were not included in the comprehensive list of MR QA tests described by the ACR. These tests assessed laser alignment with imaging isocenter, laser movement smoothness and accuracy, and laser marking accuracy. These were not included in the ACR QC Manual due to their specificity to an external laser positioning system of an MR-SIM.

General RF coil (non-flexile) testing is recommended to be tested annually by both the ACR and TG-284. Flexible RF coil performance tests were encompassed in all RF coil testing by the ACR. However, TG-284 recommends that flexible coils, specifically, be tested monthly, while rigid coils be tested annually.

4.1.1.3 DAILY QA TESTS (MR-SIM)

Seven of the eight daily MR-SIM QA tests performed by the MR technologist were included in the ACR QC Manual. The following three daily tests, ‘transmitter gain and central frequency,’ ‘spatial fidelity’, and ‘basic coil SNR’ checks were recommended to be tested less frequently by the ACR. The remaining four daily MR-SIM tests were included in the ACR’s visual checklist, which had been adapted for MR-SIM in TG-284. The visual checklist is suggested to be completed weekly by the ACR, while TG-284 did not specify frequency of visual checklist completion.

4.1.1.4 QA TEST EXCLUDED IN TG-284

Six QA tests described and required for ACR MR testing were not included in the recommended set of tests for an MR-SIM system by TG-284. Tests not mentioned in TG-284 were slice-thickness accuracy, slice position accuracy, soft-copy/monitor control, weekly completion of the visual checklist, annual review of the visual checklist, and MR safety program assessment. All tests but the weekly completion of the visual checklist were required to be performed annually by the ACR.

4.1.1.5 NEW MR-SIM QA TESTS

A total of five new tests were recommended for the MR-SIM system, including one new daily test, three new monthly tests, and one new annual test. All new tests pertained to assessing ELPS characteristics (Table 5). The new daily test was, 'external laser agreement with imaging plane.' The new monthly tests were, 'laser alignment with imaging isocenter,' 'laser alignment with imaging isocenter,' and 'laser marking accuracy.' The new annual test was, 'determine or verify external laser offset from MR isocenter.'

4.1.2 MR & MR-SIM TOLERANCES

MR QA testing tolerances recommended by TG-284 and the ACR were reviewed. QA testing tolerances that evaluated the same MR system characteristics were compared. In TG-284, 4 annual tests, 13 monthly tests, and 8 daily tests evaluated the same MR system characteristics in both a standard MR system and an MR-SIM system. 4 of these 25 tests were found to have different recommended passing tolerances and 1 test could not be compared.

LCD tolerances for an MR-SIM system were stricter than that required by the ACR for a standard MR system. TG-284 recommends that the total number of discernable spokes

in the LCD insert should be between 21 and 36 for fields less than 3 T and 40 for 3 T fields. Conversely, the ACR recommends that the total number of complete spokes be at least 7 (9 preferred) for a 1.5T magnet and at least 37 for a 3T magnet (Table 6A)

Table motion smoothness and accuracy tolerances were different in both reports. TG-284 recommends that the accuracy of the table motion should be within 1 mm while the ACR recommends that table motion accuracy be within 5 mm (Table 6B).

Transmitter gain tolerance for an MR-SIM system was suggested to be within 5% of the baseline measurement. Conversely, the tolerances for a standard MR system were not explicitly defined by the ACR. OHSU tolerances for the Philips Ingenia 3.0T MR system were substituted for comparison and were found to be different. The transmitter gain tolerance for the MR system at OHSU was required to be within 0.05 dB (6.06%) of the baseline for the 3.0T Philips Ingenia scanner.

Magnetic Field Homogeneity was required to be within 0.5 ppm over a 35 cm Diameter Spherical Volume (DSV) for an MR-SIM system. No specific homogeneity requirement was defined by the ACR for standard MR systems, but the tolerance for the 3.0 T Philips Ingenia System was less than 2 ppm over a 24 cm DSV.

Table 6A: Image Quality QA Testing Tolerances from ACR and TG-284 with Identified Differences

	Institution-Recommended Tolerances		
QA Procedure	**TG-284**	**ACR**	**Diff[c]**
Image Quality			
Geometric accuracy	± 2 mm	± 2 mm	
High contrast spatial resolution	≤ 1.0 mm	≤ 1.0 mm	
Low contrast detectability	21 to 36 spokes (< 3T), and 40 spokes for (3 T).	1.5 T at least 7 spokes (9 preferred). At least 37 for 3T	*
Artifact evaluation	No observable artifacts	No observable artifacts	
Percent image uniformity (PIU) (Head Coil)	≥87.5 for 1.5 T Magnet, ≥82.0% for 3.0T Magnet	≥87.5 for 1.5 T Magnet, ≥82.0% for 3.0T Magnet	
Percent signal ghosting	≤ 2.5 %	≤ 2.5 %	
Central Frequency	Manufacturer Specified	± 500 Hz from baseline[a]	~
Transmitter Gain	± 5% from baseline	±0.05 dB from baseline[b]	*
Flexible RF coil testing	Individual elements, exceeds minimum vendor-provided threshold	Vendor-specified	

[a]Central Frequency tolerance for 3.0T Philips Scanner at OHSU. Tolerance was not specified by ACR and depends on scanner performance.

[b]Transmitter gain tolerance is given for the Philips Ingenia 3.0T scanner at OHSU. Tolerance was not specified by ACR and depends on RF coil type and performance.

[c]Is there a difference (Diff) in QA test tolerance

~ Not comparable

* Tolerance difference identified

Table 6B: QA Testing Tolerances from ACR and TG-284 with Identified Differences

	Institution-Recommended Tolerances		
QA Procedure	**TG-284**	**ACR**	**Diff[c]**
Mechanical Tests			
Table movement smoothness and accuracy	±1.0 mm from set distances	± 5.0 mm from set distance	*
Laser alignment with imaging isocenter	±2.0 mm from expected distance offsets	NA	
Laser movement smoothness and accuracy	±2.0 mm from set distances	NA	
Patient Marking			
Laser marking accuracy	±2.0 mm	NA	
System			
Room temperature and humidity	Functional	Functional	
Cold Head Operation	Functional	Functional	
Cryogen level indicator	Functional	Functional	
Other			
Magnetic Field Homogeneity	< 0.5 ppm over a 35 cm DSV	< 2 ppm over a 24 cm DSV[d]	*
RF Coil Evaluation			
External Laser Alignment with Iso	≤ 1 mm	NA	

[c]Is there a difference (Diff) in QA test tolerance

[d]Magnetic Field Homogeneity is given for the Philips Ingenia 3.0T scanner. Field homogeneity is scanner dependent and should be defined by the QMP and service engineer.

~ Not comparable

* Tolerance difference identified

4.1.3 QA RESULTS EVALUATION

Annual QA testing on the Philips Ingenia 3.0T MR scanner was performed under the supervision of a Diagnostic Medical Physicists. Annual and weekly measurements and results were obtain using the guidelines of the ACR MR QC Manual.[13] The completed annual QA report for the MR system is included in the appendix (Appendix 8.1).

All annual MR QA tests for the MR system were within the passing tolerances defined by the ACR for a standard MR system (Appendix 8.1). For tests that were included in both TG-284[8] and the ACR guidelines,[13] and that had the same testing tolerances, it can be said that these tests would have also passed using the tolerances of TG-284.

The four tests that had different testing tolerances were further investigated to determine if the results taken from an example MR system at OHSU would be able to pass new tolerances for an MR-SIM system.

4.1.3.1 LOW-CONTRAST DETECTABILITY

Low-contrast detectability tolerances differed between the two investigated systems. For the 3.0T magnet and the ACR T1 pulse sequence (Table 3), 40 total spokes were counted in the LCD section of the Large ACR MR Phantom. For the ACR T2 weighted pulse sequence, a total of 38 complete LCD Spokes were found. The tolerance for a standard 3.0T MR system was at least 37 LCD spokes while the tolerance for a 3.0T MR-SIM system was 40 spokes. The discernable LCD spoke in the ACR T1 series were considered passing while not enough spokes were counted in the ACR T2 imaging series (Table 7).

Table 7: Low-contrast Detectability Measurements and Tolerance Evaluation

Image Series	Slice No.	Total No. of Spokes	ACR Pass[a]	TG-284 Pass[b]
ACR T1	8-11	40	PASS	PASS
ACR T2	8-11	38	PASS	FAIL

[a]ACR passing criteria for LCD was 37 or more total spokes.[13]
[b]TG-284 LCD passing criteria for a 3.0T scanner was 40 total spokes.[8]

4.1.3.2 TRANSMITTER GAIN

Transmitter gain was recorded from display on the MR scanner console. Transmitter gain was evaluated using the both ACR and TG-284 tolerances. The baseline gain from commissioning was given as 0.8252 dB. The transmitter gain for the standard MR system was required to be within 0.05 dB of the baseline value. The transmitter gain for an MR-SIM system was required to be within 5% of the baseline (Table 6).[8] It was found that the transmitter gain for the MR system was within the tolerance for standard systems by the ACR while not within the tolerance of TG-284 (Table 8).

Table 8: Transmitter Gain Measurement and Tolerance Evaluation

Baseline Meas. (dB)	Tx Gain Meas. (dB)	%Difference	Difference (dB)	ACR Pass[a]	TG-284 Pass[b]
0.8252	0.8668	5.04%	.0416	PASS	FAIL

[a]ACR transmitter gain tolerance was ± 5.0 dB from the baseline.[13]
[b]TG-284 transmitter gain tolerance was ± 5% from the baseline.[8]

4.1.3.3 TABLE MOTION

Table motion measurement values acquired during weekly QC by aligning the grid section of the Large ACR MR Phantom could not be obtained. Values were not recorded, but the table motion and positioning accuracy checks were passing and within the 5 mm tolerance for ACR guidelines.[13] Table motion was evaluated using the suggested testing method from TG-284, where the table was translated into and out of the bore 150 mm and

300 mm. The average measurements were within the 1 mm tolerance of TG-284 with an average difference in distances of 0 mm.

Table 9: MR Table Translation Measurements and Tolerance Evaluation

Dist	+150 mm	+300 mm	ACR Pass[a]	TG-284 Pass[b]
Average Distance	150 mm	300 mm	PASS	PASS

[a]ACR table motion accuracy tolerance was ± 5 mm[13]
[b]TG-284 table motion accuracy tolerance was ± 1 mm[8]

4.1.3.4 MAGNETIC FIELD HOMOGENEITY

Magnetic field homogeneity over a 35 cm DSV was not measured. Instead, the homogeneity over a 24 cm DSV was measured for the Philips Ingenia 3.0T MR scanner. The magnetic field homogeneity over the 24 cm DSV using the bandwidth difference method was measured to be 0.186 ppm in the axial direction, 0.311 ppm in the sagittal direction, and 0.218 ppm in the coronal direction (Table 10). These values were below the 2 ppm tolerance set by OHSU and was also within the 0.5 ppm tolerance set for MR-SIM systems by TG-284, but is not considered a direct comparison because of DSV size differences.

Table 10: Magnetic Field Homogeneity (MFH) and Tolerance Evaluation

	Diameter of Sphere (mm; BW1[a], BW2[b])		MFH (ppm)	ACR Pass[d]	TG-284 Pass[e]
Axial	239.0	239.6 mm	0.186	PASS	NA
Sagittal	239.9	238.9 mm	0.311	PASS	NA
Coronal	239.4	240.1 mm	0.218	PASS	NA

[a]Bandwidth measurement 1
[b]Bandwidth Measurement 2
[c]ACR MFH passing tolerance was < 2 ppm over a 24cm DSV for the Philips Ingenia 3.0T scanner
[d]TG-284 passing tolerance was <0.5 ppm over a 35 cm DSV.

5. DISCUSSION

The results of this work have shown the similarities and differences between QA tests for standard MR systems and MR-SIM systems. Through reviewing QA guidelines for each system[2 3 8 13], it was determined that only five new tests were required for the MR-SIM system and only six tests from ACR were not specified for an MR-SIM system. The majority of tests were found to have different testing frequencies with the exception of four annual tests.

5.1 EXCLUDED QA TESTS (MR-SIM)

Six QA tests required for ACR MR accreditation were excluded from the list of tests for an MR-SIM system, in TG-284. The six tests were soft-copy luminance testing, slice position accuracy, slice thickness accuracy, completion of the visual checklist, review of the visual checklist, and assessment of the MR safety program. Reasons for excluding these tests were not mentioned in the scope of TG-284 and may need to be addressed on a case-by-case basis. The qualified medical physicists should determine if these tests should be performed and if the tolerances should be different than ACR recommended tolerances.

Soft-copy luminance testing was not required for MR-SIM systems. This test assures that the electronic display devices such as computer monitors are functioning appropriately and ensures proper viewing of DICOM files and acquired MR images. Even though this test has been excluded from TG-284 and MR-SIM testing, soft copy maintenance and QC is already a required duty of the medical physicist as per the AAPM Task Group 18 report 03, “Assessment of Display Performance for Medical Imaging Systems.” Thus, this test has originally been excluded by TG-284 but should be performed regularly on both the MR console as well as the physicians’ workstations.

Slice position accuracy and slice thickness accuracy were also excluded for MR-SIM testing requirements and were not included in the scope of TG-284. Reasons for excluding these tests are unclear, especially considering that specialized inserts to test these metrics are included in the ACR MR Phantom, which is required for many MR-SIM QA tests (Table 2). It may be recommended to include these tests and to follow the tolerances specified for standard MR systems by the ACR.

Completion of the visual checklist and an annual review of the visual checklist is required as part of ACR MR Accreditation. However, these QA tests have not been explicitly included as part of routine QA testing in TG-284. Furthermore, the visual checklist was included as part of TG-284, but a testing frequency was not suggested. The Medical Physicists should decide if the visual checklist should be included as part of routine QA and QC, and decide how often the visual checklist needs to be completed and reviewed.

The last test excluded from TG-284 was an annual review of the MR Safety Program. The MR safety program details the necessary safety components of operating an MR system, including MR safety zones, patient safety and screening procedures, emergency equipment and protocols, and more. In both ACR and TG-284, a description of an MR safety program is included. An annual review of the MR safety program is required for ACR accreditation, but not specifically mentioned in TG-284. Similar to other excluded tests, the medical physicist should determine if an MR safety program review should be performed annually.

5.2 TESTING FREQUENCY DIFFERENCES

Testing frequencies for the MR-SIM were different for all tests except four annual tests. In general, the weekly ACR QC tests were most similar to the daily tests of TG-284 (Table 5A/B) because they were to be performed by technologists rather than physicists. Furthermore, weekly QC tests performed by technologists for ACR testing included low-contrast detectability, high-contrast detectability, the visual checklist and a visual inspection of images for artifacts. These tests were included in TG-284 but were recommended to be performed monthly by the Medical Physicists. Thus, the overall frequency that LCD, HCD, the visual checklist, and artifact evaluation would all be performed less frequently for MR-SIM systems than a standard MR system.

A potential reason for daily testing frequency for MR-SIM systems may be due to how frequently the MR-SIM system is used in the clinic. Diagnostic MR systems at OHSU have a very heavy workload and are used daily as well as weekends. For dedicated units that are only used by the radiation oncology department, MR-SIM systems may not be used every day and may be in a standby mode more often. Performing daily tests instead of weekly tests may be suggested to ensure that performance meets requirements on the days that the machine is in use.

5.3 TESTING FREQUENCY CLINICAL IMPACT

MR QA testing is a time-consuming process. The estimated time to complete weekly ACR MR QA is 33 minutes, while annual ACR MR QA testing may take several hours.[13] Increasing the testing frequency of some tests from weekly and annually to daily and monthly, respectively, significantly increases the workload of MR Technologists and Medical Physicists while reducing the patient throughput on the machine. Already at OHSU, reserving time to perform annual QA tests on diagnostic MR systems is a

challenge. The ability to perform tests more frequently for MR-SIM systems may be greatly affected by the workload and availability of the machine.

5.4 NEW QA TESTS (MR-SIM)

All five of the new tests assessed the characteristics and functionality of an external laser positioning system – which is equipment specific to MR-SIM systems and for radiation oncology treatment planning purposes. These QA tests are meant to verify the coincidence of the ELPS isocenter and MR isocenter which is important for patient marking and creating a reproducible setup for treatment delivery.

An ELPS is not the only new equipment or design feature specific to MR-SIM systems. Patient exam tables with a flat tabletop are necessary for appropriate simulation. Exam tables must be able to translate smoothly and accurately to produce precise images with minimal localization error. Because of this, table motion smoothness and accuracy QA tests for an MR-SIM had stricter tolerances than tables used for standard MR systems. For normal systems, the table position was required to be within 5 mm of the set distance, while MR-SIM table motion had to be within 1 mm of the set distance. The procedures used to test these parameters were different in both systems. For MR-SIM systems a direct measurement of table motion was performed using a ruler. Conversely, ACR table motion was measured on the MR system display console. These variations in measurement type may contribute to greater differences in measured table motion on both systems. A direct measurement of table motion using a ruler is more accurate than using acquired images and can be used to measure a range of distances to evaluate table motion accuracy over longer ranges.

5.5 ACR ACCREDITATION OF MR-SIM

It is possible to obtain ACR MR Accreditation for an MR-SIM system, especially since much of the major imaging equipment is the same. If this were to happen, a decision on which testing regimens to follow would have to happen. However, to become ACR certified, QA tests, tolerance, and testing frequency from the ACR would have to be followed, at a minimum. This would require the addition of the 5 omitted tests to MR-SIM QA testing. Prepended tests for ACR certification include slice position accuracy, slice-thickness accuracy, weekly visual checklist completion, annual safety program review, and annual soft-copy luminance testing.

Most tests in TG-284 were recommended to be tested more frequently, which would ensure that minimum testing frequencies for ACR accreditation were met. Exceptions to this were weekly ACR image quality QC tests and monthly flexible RF coil testing (Table 6B). As recommended for MR-SIM systems by TG-284, flexible RF coil testing should be completed monthly instead of annually (Table 6B).

ACR MR Accreditation should be obtained for MR-SIM systems. ACR accreditation is a required certificate for some insurance coverage. Additionally, the purpose of ACR accreditation is to ensure that the images produced are from a safe machine that can produces images of a good enough quality to make accurate diagnosis.

5.6 FUTURE WORK

Further research is needed to completely assess the MR scanners used for radiotherapy treatment planning at OHSU. Magnetic field homogeneity measurements for TG-284 required using a 35 cm DSV. Measurements should be performed using the larger phantom to assess homogeneity across a larger region of space. Homogeneity is known to

be worse further from the imaging isocenter which can be measured using phantoms larger than the 24 cm DSV used for some routine MR testing procedures at OHSU.

QA testing on a wide-bore standard MR system should also be performed for a more accurate representation of MR-SIM equipment. MR-SIM systems require a wide-bore to enable specific patient positions as well as immobilization devices. Wide bore systems are susceptible to worsened image quality and may have different image quality and system performance characteristics that should be considered when using these images for RT treatment planning.

Finally, an evaluation of MR pulse sequences used for treatment planning should be performed. A wide variety of pulse sequences are used for visualizing specific anatomical information and guiding treatment decision making. Certain pulse sequences may have increased susceptibility to geometric distortion artifacts (i.e. gradient echo sequences) or other image quality degradations. A potential method for mapping total distortion in patients from a specific scan has been described by Balter et. al. using phase information from an MR scan.

6. CONCLUSION

QA testing differences from the ACR's standard MR system QA guide[13] and from the TG-284 MR-SIM QA testing guide were determined for a commercial diagnostic MRI scanner at OHSU. It was determined that all but six tests recommended for standard MR systems were included in QA testing for TG-284. Five MR-SIM specific QA tests were identified, and at least four notable changes to QA testing tolerances were made for MR-SIM systems. The results from a standard MR-SIM system were evaluated using MR-SIM and standard MR system tolerances. Table motion accuracy from the standard MR system

at OHSU was considered passing with the 1 mm and 5 mm passing tolerances of TG-284 and the ACR, respectively. Low-contrast detectability measurements for the 3.0 T scanner were 40 total spokes for an axial T1 sequence and 38 total spokes for an axial T2 sequence. LCD passed the 37 total spoke tolerance of the ACR, but partially failed to meet the 40 total spoke requirement for MR-SIM systems by TG-284 standards. Transmitter gain measurements for the 3.0T system were within the 0.5 dB tolerance from the ACR but failed to meet the 5% difference tolerance of TG-284 for MR-SIM systems. This evaluation of QA tests has identified proposed differences to MR-SIM QA tests from TG-284. It has shown that many tests are the same between an MR-SIM system and standard diagnostic MR system, but that testing is recommended to be performed more frequently and four tests were required to have more strict tolerances.

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APPENDIX

1. Annual MR QA Report Documents and Tables

Philips 3.0T Ingenia
DCH MRI2 (SN: 71556)

OREGON HEALTH & SCIENCE UNIVERSITY

Department of Diagnostic Imaging

Annual Testing Report

Tested by:
Celeste Leary, Ph.D and Jacob Buatti

Guidance, Supervision, and Review by:
Isaac Bailey, M.S.

on
Monday, November 23, 2020

Annual Testing Report
Oregon Health and Science University
Dornbecher Children's Hospital
MRI2: Philips 3.0T Ingenia
Monday, May 23rd, 20201

Table A1: Annual MRI System Performance Evaluation

	Test	Result
1.	**ACR Phantom Tests**	***Pass***
	Setup and Table Position Accuracy	*Pass*
	Geometric accuracy	*Pass*
	High contrast spatial resolution	*Pass*
	Slice position accuracy	*Pass*
	Slice thickness accuracy	*Pass*
	Image intensity uniformity	*Pass*
	Percent signal ghosting	*Pass*
	Low contrast object detetectability	*Pass*
	Artifact Evaluation	*Pass*
2.	**Magnetic Field Homogeneity**	***Pass***
3.	**Monitor Performance**	***Pass***
	Visual Analysis	*Pass*
	Photometric Analysis	*Pass*
4.	**Laser Film QC**	***N/A - filmless***
5.	**Center Frequency and Transmitter Gain**	***Pass***
6.	**Visual Checklist**	***Pass***
7.	**Safety Program Assessment Checklist**	***Pass***
8.	**Weekly Technologist QC**	***Pass***
9.	**RF Coil Performance**	***Pass***
	Volume coils' image uniformity	*Pass*
	Volume coils' ghosting ratio	*Pass*
	Surface coils' signal-to-noise ratio	*Pass*

Signed: Isaac J Bailey
Date: 11/23/2020

Comments: This unit passes all tests conducted during the annual performance evaluation.

Until DCH MRI2
MRAP #: 04898-09
ACR Phantom SN: J13051

Table A2: RF Coil Testing Results

Equipment	
Manufacturer:	Philips
Model:	3.0T Ingenia
Magnet SN:	71556
Software Version:	5.3.1
Film Printer:	N/A
Transmitter Gain:	0.8668
Center Freq MHz (±500)	127.762015

RF Coil Testing*	
Volume Coils	**Result**
DS Head Coil	Pass
DS Head/Neck	Pass
T/R Head	Pass
DS Small Extremity 8 ch	Pass
DS T/R Knee 16 ch	Pass
DS Foot/Ankle 8 ch	Pass
DS Peds Head/Spine 8 ch	Pass
DS Wrist 8 ch	Pass
DS Shoulder 8 ch	Pass
Surface Coils	**Result**
DS Anterior Coil	Pass
Result	***Pass***

*All coils are manufactured by Philips. Please see attached coil testing documentation at the end of this report for complete results.

Table A3: Setup and Table Position Accuracy

Setup and Table Position Accuracy	
Is Table positioning/Laser Light Alignment within +5 mm?	***Yes***
Result	***Pass***

Table A4: Geometric Accuracy Window and Level Display Settings

Geometric Accuracy		
	Sagittal Localizer	Axial T1
WINDOW	1	1
LEVEL	1129	1221
	SET:	
WINDOW	1129	1221
LEVEL	564.5	610.5

Table A5: Geometric Accuracy

Slice	Measurement	Actual Distance (mm)	Measured Distance (mm)	Difference (mm)	Result
Localizer	top to bottom	148	146.8	1.2	*Pass*
Slice 1	top to bottom	190	190	0	*Pass*
Slice 1	left to right	190	189	1	*Pass*
Slice 5	top to bottom	190	190.3	-0.3	*Pass*
Slice 5	left to right	190	188.9	1.1	*Pass*
Slice 5	diagonal	190	190	0	*Pass*
Slice 5	diagonal	190	189	1	*Pass*
Result					*Pass*

ACR Tolerance: ±2 mm

Table A6: Artifact Evaluation

Artifact Analysis	
Artifacts visible on ACR sagittal locator?	*No*
Artifacts visible on ACR T1?	*No*
Artifacts visible on ACR T2?	*No*
Result	*Pass*

Table A7: High Contrast Spatial Resolution

High Contrast Spatial Resolution			
Image Series	**Upper Left Holes (mm**	**Lower Right Holes (mm)**	**Result**
ACR T1	1.0	1.0	***Pass***
ACR T2	1.0	1.0	***Pass***
Result			***Pass***

Acceptability Criteria:
Four holes of 1.0 mm diameter in a row and in a column must be visible as separate objects. Both ACR Series or both Site Series must pass.

Table A8: Slice Position Accuracy

Slice Position Accuracy				
Series	Slice	Bar Length Difference (mm)	Slice Displacement (mm)	Result
ACR T1	1	2.1	1.05	***Pass***
	11	-2.9	-1.45	***Pass***
ACR T2	1	1.4	0.7	***Pass***
	11	-1.8	-0.9	***Pass***
Result				***Pass***

Acceptability Criteria:
The measured bar length difference must be < or equal to 5 mm.

Table A9, A10: T1 and T2 Slice Thickness Accuracy Tests

T1 Slice Thickness Accuracy				
Top ROI:	224	Window:	1	
Bottom ROI:	226	Level:	112.5	
Series	Top Length	Bottom Length	Slice Thickness (mm)	Result
ACR T1	53	54.3	5.36	***Pass***

T2 Slice Thickness Accuracy				
Top ROI:	122	Window:	1	
Bottom ROI:	126	Level:	62	
Series	Top Length	Bottom Length	Slice Thickness (mm)	Result
ACR T2	51.1	54.5	5.27	***Pass***

Acceptability Criteria:
The measured slice thickness must be 5 mm +/- 0.7 mm.

Table A11: Image Intensity Uniformity

Image Intensity Uniformity					
Image Series	**Slice**	**Low-Signal MPV**	**High-Signal MPV**	**Percent Integral Uniformity**	**Result**
ACR T1	7	1490	1949	86.7	***Pass***
ACR T2	7	910	1072	91.8	***Pass***
Result					***Pass***

Acceptability Criteria:
For magnets with field strength less than 3T, PIU should be greater than or equal to 87.5 %. For 3T PIU must be > or equal to 82 %.

Table A12: Percent Signal Ghosting

Percent Signal Ghosting		
	MPV	**Result**
Large ROI	1789	
Top	1.407	
Bottom	2.815	
Left	2.815	
Right	2.815	
Ghosting Ratio	**0.000393516**	***Pass***

Table A13: Low-contrast Detectability

Low Contrast Object Detectability			
Image Series	**Slice**	**Spokes Detected**	**Result**
ACR T1	11	10	
	10	10	
	9	10	
	8	10	
	Total	*40*	***Pass***
ACR T2	11	10	
	10	10	
	9	10	
	8	8	
	Total	*38*	***Pass***
Result			***Pass***

Acceptability Criteria: The total # of spokes observed in both of the two ACR Series or both of the Site Series must total at least 9 for < 3T, for 3T 37 is required.

Table A14: Magnetic Field Homogeneity

MAGNETIC FIELD HOMOGENEITY

Setup	
Method Used:	"Bandwidth-Difference"
Type of Phantom Used:	24cm Sphere (Siemens)

Measurements			
Plane	**Diameter of Sphere (mm; BW1, BW2)**		**MFH (ppm)**
Axial	239.0 mm	239.6 mm	0.186
Sagittal	239.9 mm	238.9 mm	-0.311
Coronal	239.4 mm	240.1 mm	0.218
Result			***Pass***

Please see final page of report for field homogeneity assessment provided by vendor.

Note: This test is performed via the technique outlined by Chen et al. using the varying bandwidth methodology. A large sphere is placed at isocenter within the magnet, either in the internal bore itself or in the largest body coil provided, depending on the magnet design. Images are acquired using a gradient echo, which is most susceptible to changes within the magnetic field. The techniques are maintained with a TR and TE as low as possible, a flip angle of 25 degrees, 1 slice at 5 mm thick with a matrix of 256x256. The time of the scan is typically less than 25 seconds with a total of 6 scans being run. First, the spherical phantom is run at a low bandwidth (measured in HZ) in the axial plane and then keeping the phantom in the exact same location, with all other parameters unchanged, an additional scan is run at a high bandwidth. This is repeated in the sagittal and coronal planes. The distance of the sphere is then measured in all 6 scans in mm and the resultant math displays the homogeneity in ppm.

Table A15: Soft-Copy Luminescence

Gray Level Performance of CT Acquisition Display Monitors

VISUAL ANALYSIS	
Appropriate gray level progression?	*Yes*
5% and 95% patches visible?	*Yes*
Finest line pair patterns visible in center and each corner?	*Yes*
Image free of bleed-through?	*Yes*
All high-contrast borders straight?	*Yes*
Is image free of geometric distortion?	*Yes*
	Pass

PHOTOMETRIC ANALYSIS				
Monitor Brightness Measurements (cd/m^2)				
			this year	*last year*
center	*189.3*	*0% step*	0.21	0.342
bottom left	*183.4*	*20% step*	5.17	5.364
bottom right	*184.3*	*50% step*	40.4	37.9
top left	*190.8*	*80% step*	114.2	98.7
top right	*189.5*	*100% step*	189.3	188.6
Minimum brightness less than 1.2 cd/m^2?			*Pass*	
Maximum brightness greater than 90 cd/m^2?			*Pass*	
Response curve similar to previous year?			*Yes*	
Degree of display nonuniformity?			*4%*	*Pass*
Result			*Pass*	

Table A16: Visual Checklist

VISUAL CHECKLIST

Patient Transport & Magnet	
Bed Position and other lights	Pass
Alignment light	Pass
High tension and other cables	Pass
Horizontal motion smoothness and stability	Pass
Filming & Viewing	
Laser printer	N/A
Light boxes	N/A
RF Integrity & Control Room	
RF Door Contacts	Pass
RF window screen integrity	Pass
Operator consolw	Pass
Patient monitors	Pass
Patient intercom	Pass
Room temperature and humidity	Pass
Facility Safety	
Emergency cart	Pass
Safety warning signage	Pass
Door indicator switch	Pass
Cryogen level indicator	Pass
Result	***Pass***

Table A17: MR Safety Program Assessment

MRI Safety Program Assessment Checklist

The site's written MRI safety policy addresses the following:	
Designated MR medical director	Yes
Site access restrictions (MR zones)	Yes
Documented MR Safety education/training for all personnel	Yes
Patient and non-MR personnel screening	Yes
Pediatric patients	Yes
Magnet quench	Yes
Cryogen safety	Yes
Acoustic noise	Yes
Pregnant patients and staff	Yes
Contrast agent safety	Yes
Sedations	Yes
Thermal burns	Yes
Emergency code procedures	Yes
Device and object screening	Yes
Designation of MR safe/MR conditional status	Yes
Reporting of MR safety incidents or adverse incidents	Yes
Patient communication	Yes
Infection control and medical waste	Yes
ACR Criteria for compliance:	
Written policies are present and readily available to facility staff.	Yes
Written policies are reviewed and updated on a regular basis.	Yes
Facility has appropriate MR safety warning signage and methods of controlled access.	Yes
Result	***Pass***

Table A18: Evaluation of weekly technologist tests

EVALUATION OF SITE'S TECHNOLOGIST QC PROGRAM

Weekly Tasks	
1. Set up and positioning accuracy - Table Positioning, Setup & Scanning	Pass
2. Center frequency	Pass
3. Transmitter attenuation or gain	Pass
4. Geometric accuracy measurements	Pass
5. Spatial resolution measurements	Pass
6. Low contrast detectability	Pass
7. Film quality control	Pass
8. Visual checklist	Pass
9. Artifact	Pass
Result	***Pass***

Table A19: RF Coil Tests

Radiofrequency Coil Checks

Coil	Serial Number	slice plane	Phantom	FOV (mm)	Mean Signal	Max Signal	Min Signal	Bkgrd Signal	Noise SD	Ghost Signal	SNR	Percent Image Uniformity	Percent Signal Ghosting
Volume Coils													
DS Head Coil	5852	axial	3000cc	250	1425.5	1673	1176	6.6	2.9	7.9	492	82.555	0.046%
DS Head/Neck	15	axial	3000cc & 2000cc	230	1544	1753	1146	7.8	2.75	9.1	561	79.062	0.042%
T/R Head	77	axial	5000cc	230	1762	1843	1702	12.6	5.4	13.8	339	96.023	0.034%
DS Small Extremity 8ch	1369	axial	small extremity	230	1608	1997	1020	3.7	2	9.7	804	67.617	0.187%
DS T/R Knee 16ch	607	axial	knee	160	1561	1745	1368	2.7	1.6	6.8	976	87.889	0.131%
DS Foot/Ankle 8ch	212	axial	foot	150	1126	1698	912	2.7	3.6	5.4	313	69.885	0.120%
DS Wrist 8ch	600	cor	wrist	400	1253	1682	822	38	6.4	49	196	65.655	0.439%
DS Shoulder 8ch	1108	axial	shoulder	200	1493	1822	1049	2.8	3.6	6.9	415	73.076	0.137%
Surface Coils													
DS Anterior Coil	96	axial	3000cc	230		1569			3.7		424		