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Task Group 284 Report: Magnetic Resonance Imaging Simulation in Radiotherapy: Considerations for Clinical Implementation, Optimization, and Quality Assurance

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Disclosure Statement

The Chair of the AAPM Task Group 284 has reviewed the required Conflict of Interest statement on file for each member of AAPM Task Group 284 and determined that disclosure of potential Conflicts of Interest is an adequate management plan. Disclosures of potential Conflicts of Interest for each member of AAPM Task Group 284 are found at the close of this document.

Abstract

The use of dedicated magnetic resonance simulation (MR-SIM) platforms in Radiation Oncology has expanded rapidly, introducing new equipment and functionality with the overall goal of improving the accuracy of radiation treatment planning. However, this emerging technology presents a new set of challenges that need to be addressed for safe and effective MR-SIM implementation. The major objectives of this report are to provide recommendations for commercially available MR simulators, including initial equipment selection, siting, acceptance testing, quality assurance, optimization of dedicated radiation therapy specific MR-SIM workflows, patient-specific considerations, safety, and staffing. Major contributions include guidance on motion and distortion management as well as MRI coil configurations to accommodate patients immobilized in the treatment position. Examples of optimized protocols and checklists for QA programs are provided. While the recommendations provided here are minimum requirements, emerging areas and unmet needs are also highlighted for future development.

TABLE OF CONTENTS

1. INTRODUCTION

Modern radiation treatment planning (RTP) requires images of high geometric fidelity with high spatial and contrast resolution to delineate disease extent and proximity to adjacent organs at risk. When compared to other imaging modalities, magnetic resonance imaging (MRI) demonstrates superior soft tissue contrast that substantially improves target and organ at risk (OAR) segmentation accuracy and reliability[1-10]. Evidence suggests that incorporating MRI in RTP (1) reduces treatment-related toxicities due to dose reductions of more accurately delineated OARs[11-18] while (2) identifying regions of high tumor burden to facilitate dose escalation[16,19-21]. However, when clinically indicated, today's conventional CT simulation (CT-SIM) based workflow for many disease sites relies on target and organ at risk definition on MRI followed by a transfer of contours to CT via image registration. This co-registration process may introduce geometrical uncertainties of ~2 mm for the brain[22,23] and pelvis[24,25], and up to 5 mm in the abdomen[26] including the impact of differing patient postures due to the absence of immobilization devices, treatment accessories, or treatment devices used during CT-SIM. Importantly, these errors are systematic, persist

throughout treatment, may shift high dose regions away from the target[27] and could potentially lead to a geographic miss that compromises tumor control. In addition, MR images are often used without consideration of intrinsic geometric fidelity, an approach that may increase the uncertainty beyond co-registration errors and adversely impact dosimetric endpoints. For example, Adjeiwaah *et al*. estimated a small difference (< 0.5%) in the PTV dose in prostate cancer patients arising from residual system and patient induced susceptibility distortions[28]. Likewise, susceptibility induced voxel displacements in a cohort of 19 brain cancer patients scanned on a 3.0 T scanner were <1 mm for ~97% of the voxels evaluated[29]. In cases with smaller targets, geometric accuracy becomes a more critical issue, e.g. for a target size of 3 cm, geometric distortions of 1.5 mm may impact the dose to 95% of the volume[30]. For lateral disease sites such as the breast, 8 out of 18 whole-breast treatment plans accounting for patient and systematic distortions were deemed clinically unacceptable when assessed on the original CT[31]. Overall, the dosimetric impact from distortions will depend on factors such as the distance of the anatomy from magnet isocenter, magnetic field strength, and MRI acquisition parameters as will be described in this report.

To address these limitations, Radiation Oncology dedicated MR simulator platforms have been recently introduced to facilitate the MR simulation (MR-SIM) process, adding equipment and functionality with the overarching goal of improving the accuracy of target and OAR delineations required for RTP[32,33]. In this Task Group, MR-SIM is defined as the acquisition of MR images of a patient that fulfill the needs for Radiation Oncology treatment planning including (but not limited to) acquiring data: in the treatment position using dedicated equipment, at the physiological state of interest (i.e., breath-hold), with high spatial fidelity, large fields of view, high resolution, and with optimized sequences. The equipment used to perform this task will be termed in this TG as an MR simulator. In this TG report, consideration is given to both Radiation Oncology dedicated vs. shared resources with Diagnostic Radiology as described in Section 2.1.1. While the current scope of the TG makes the underlying assumption that CT-SIM datasets will also be obtained, this concept can be applied in future development for MR-primary treatment planning. This emerging technology presents a new set of staffing, QA, and workflow challenges that need to be addressed for effective implementation.

1.1 Purpose

The focus of the current TG report is the radiotherapy-specific aspects of MR-SIM for external beam radiation therapy, including both the use of MR images to support delineation of anatomic structures for RTP in conjunction with CT, as well as using MR images to support RTP as a primary modality.

1.2 Goals

The specific charges for the TG are as follows:

1. Define the requirements of an MR simulator including considerations for equipment selection, facility design and siting, and personnel and their roles;
2. Describe general, patient-specific, and device MR safety considerations;
3. Provide recommendations on RT-specific MR clinical workflows and acquisition protocols, including approaches for distortion mitigation and motion management;
4. Outline recommended acceptance, commissioning and periodic QA for MR simulators (with emphasis on RT-specific QA tasks), including defining the personnel effort required.

The scope of this task group is limited to considerations for external beam radiation therapy and will not focus on MR for brachytherapy, functional imaging/response assessment, MR-only planning, on-board MRI or MRI-simulation for IGRT (e.g., MR-linacs), or stereotactic radiotherapy procedures.

1.3 Rationale

MRI is playing an enhanced role in radiation therapy (RT) planning[34]. As the use of MRI in RT increases, the demands for acquiring MR data with higher spatial and contrast resolution will continue to increase. Nearly all clinics use MR images in their treatment planning workflows, and many of these images have not been optimized for RTP purposes. The imaging requirements for RTP present a new set of challenges and introduce additional constraints on MRI compared to Diagnostic Radiology that, if not addressed, can undermine the advantages MRI offers for RTP. This TG will summarize and consolidate recommendations to yield general principles and specific guidance for vendor-neutral implementation of MR-SIM across multiple field strengths, with the overarching goal of enabling recommendations to be generalizable and adaptable as future platforms become available to the community.

1.4 Nomenclature and definitions

3D: Three-dimensional

4D: Four-dimensional

ACR: American College of Radiology

CON: Certificate of Need

CT-SIM: Computed Tomography Simulation

DSV: Diameter spherical volume

DWI: Diffusion-weighted Imaging

ELPS: External Laser Marking and Positioning System

EPI: Echo-planar imaging

FDA: Food and Drug Administration (United States)

GBCA: Gadolinium-based Contrast Agent

GNL: Gradient Non-linearity

GRE: Gradient Echo

IEC: International Electrotechnical Commission

MR-SIM: Magnetic Resonance Simulation

QA: Quality Assurance

QMP: Qualified Medical Physicist[1]

RF: Radiofrequency

RT: Radiotherapy

SAR: Specific Absorption Rate

SNR: Signal to Noise Ratio

2. BACKGROUND AND OVERVIEW OF MR-SIM

2.1 Equipment selection and program considerations

While MR simulators in Radiation Oncology are increasingly used in large comprehensive cancer centers, potential impediments to its general utilization in RT include cost, limited access to technology, and limited technical expertise needed for initial implementation of RT-specific goals and ongoing utilization.

2.1.1 Radiation Oncology dedicated vs. shared resources

The overall cost of an MR-SIM system largely depends on the field strength, technical specifications, room size/cost considerations, and options of the system selected. While there are business plans that can support a dedicated MR simulator in Radiation Oncology Departments, some centers opt to make the system a shared resource with Diagnostic Radiology. A shared resource may be more economical, improve overall patient volumes and throughput, utilize institutional MR expertise, and support pulse sequence selection optimal for delineation of structures for RTP. However, a shared resource may require compromises in equipment selection such as magnet specifications, coil design, and implementation of 3D gradient non-linearity (GNL) distortion correction. To improve integration into RT treatment planning, auxiliary equipment such as flat table tops, integration of immobilization devices, and external localizing lasers are required. Furthermore, the MR scanner must meet the quality assurance criteria outlined in Section 6. Shared use models should consider fundamental differences in workflow between departments. Radiation Oncology may have a relatively small number of patients imaged per day compared to Diagnostic Radiology, but immediate access to the scanner may be critical (e.g., stereotactic radiosurgery, brachytherapy procedures with patients under anesthesia, etc.). Additionally, room utilization may include

[1]QMP as defined in AAPM Professional Policy 1. Definition of a Qualified Medical Physicist. Available from: http://www.aapm.org/org/policies

fabrication of immobilization devices, waiting for physician review of images and performing target delineation, and applying tattoos to the patient's skin for reference localization. The length of procedures and timeliness for access should be considered with scheduled scanner time essential to maximize throughput and minimize physiological status changes (e.g., OAR filling differences) between CT and MR simulation. The impact of implementing an MR-SIM as a dedicated or shared resource will influence the clinical utilization of the system, and consequently several practical and technical details that are highlighted throughout this report.

2.1.2 Certificate of Need (CON)

An additional limitation to access may be the Radiation Oncology Department receiving a CON for the system. CON programs were established to restrain health care facility costs and promote coordinated planning of new technology acquisition and facility construction. CON laws at the state level were established in response to the federal "Health Planning Resources Development Act" of 1974. While there have been numerous changes in the past 40 years, the majority of states (36) continue to require a CON for the purchase of an MRI scanner.

2.1.3 Bore size, configuration, and magnetic field strength

Bore size, configuration, and field strength must be an early consideration. While increasing bore size can negatively impact image quality in certain high-performance sequences (e.g. diffusion, diffusion tensor), wide-bore (i.e., ≥70 cm) scanners are critical for MR-SIM to accommodate immobilization devices and elaborate patient positioning techniques used in radiation therapy. The vast majority of bores have a cylindrical design, although "open" bore magnets with vertical magnetic field designs are available[32] that enable translation of the patient laterally to center the anatomy of interest close to the magnet isocenter. Open platforms have wide apertures (>150 cm) that may be advantageous for scanning larger patients, however they often are of lower field strength (0.23T[13,35] and 1.0T[32]). In addition, larger magnitudes of geometric distortion at extended fields of view have been reported relative to cylindrical wide bore MR-SIMs.[36] Considerations for bore size include the additional thickness of the immobilization device, protruding extremities, overall body habitus, and the further displacement of the patient from the center of the scanner's field of view (FOV) that can introduce/amplify image artifacts and geometric distortions. For example, patients positioned prone with either a belly board or breast board will be elevated within the bore. The diameter of the useable FOV will ideally capture the full patient anatomy, including the skin surface, with minimal distortion of the skin surface so that accurate radiological path lengths and source to skin distances can be determined. It should be noted that the maximum FOV will be limited by the magnet geometry, field homogeneity, and the RF coil coverage.

Magnetic field strength is a more nuanced consideration with comparisons available in the literature[37-39]. In brief, selection of field strength may be driven by capital costs, construction/shielding requirements, and operational expenses, which all increase with field strength, as well as intended clinical utilization, patient population, and technical expertise available at the institution. High field strength yields higher SNR and increased spatial resolution, as well as increased acceleration factors to reduce scan times[40], however higher field strengths also pose additional challenges when scanning patients with metal implants due to the risk of local heating and increased susceptibility artifacts. Alternatively, lower field strength systems demonstrate reduced geometric distortion, chemical shift, and specific absorption rate (SAR).

2.1.4 Technical specifications for the magnet

MR-SIM vendors will provide technical specifications for each platform that should be taken into consideration when selecting equipment. The maximum (peak) gradient strengths are typically on the order of 35-80 mT/m. Slew rate (e.g., 200 T/m/s), defined as peak gradient strength divided by the rise time (typically 0.1-0.3 ms) will impact the minimum repetition time (TR) and echo time (TE) for acquisition while also impacting the echo spacing for fast spin echo and echo-planar imaging (EPI) acquisitions. Slew rate impacts the readout bandwidth, a critical parameter to reduce geometric distortions with standard imaging, while faster slew rates shorten effective echo times thereby reducing geometric distortions in EPI-based diffusion-weighted imaging (DWI). Slew rate and gradient strengths may be reported on the X, Y, and Z axis independently or combined via an "effective" value that should be taken into consideration when comparing platforms. Having stronger gradients and higher slew rates is advantageous for high-performance imaging such as that used in diffusion-weighted and functional imaging applications.

The vendor will also provide specifications of large FOV magnetic field homogeneity. Notably, the manufacturer's specifications are reported in parts per million (ppm) over a certain diameter spherical volume (DSV). Vendors often quote the "linearity" (i.e., gradient non-linearity (GNL) described in detail in Section 6.2.2) in a percentage over the FOV. It is strongly recommended that high-order GNL corrections and high-order shimming (i.e., 3 first-order linear channels, 5 second-order non-linear channels) are considered to ensure high precision RT[29]. When comparing manufacturers' specifications for different MR-SIM platforms, the reported DSV and FOV extents must be taken into consideration as field inhomogeneity and GNL distortions both increase nonlinearly as the DSV/FOV increases.

2.2 Major MR simulator equipment

Ideally, patient positioning during MR-SIM should mimic that for CT-SIM and treatment. However, many older diagnostic MRI scanners have curved couch tops and standard equipment that are not designed to meet the needs of Radiation Oncology. Table 1 summarizes the major MR simulator equipment, typical functions, and recommendations/considerations.

Figure 1 highlights typical considerations for patient setup for placing the anterior surface coil from the RF coil bridge and configuring the flat table overlay with immobilization devices. In this example, the RF coil is integrated into the couch; however, alternate configurations include placing a posterior surface coil below the flat table overlay, on top of the flat table overlay, or embedded within the immobilization devices, with tradeoffs between SNR and distance between the coil and the patient. Note that the flat table overlay and/or inserts may increase the total weight of the table and thus impact the weight limit tolerance for imaging patients on the MR-SIM. Ideally, for MR-SIM, flat table tops would be affixed much like in CT simulation and treatment delivery systems to achieve the same level of mechanical stability and performance. However, the majority of industry offerings include detachable/dockable tables for the advantages outlined in Table 1, with some centers housing two such trolleys for patient transfer and throughput.

3. CONSIDERATIONS FOR FACILITY DESIGN AND SITING OF AN MR SIMULATOR

Successful integration of an MR simulator suite into a Radiation Oncology department begins with facility design and siting of the MR scanner, thus it is imperative for medical physicists (ideally a combination of an MRI-trained diagnostic and a therapy physicist or a minimum of one MRI-trained diagnostic physicist as outlined in Table 2) be involved at early phases of design to (1) provide necessary technical expertise, (2) identify workflow and siting issues, and (3) highlight equipment specifications for designing the MR simulator suite.

3.1 Zoning/Site access restriction

The majority of new MR scanners are superconducting high field ($\geq$ 1.5 T) systems in which the main magnetic field (B_0) is permanently maintained following installation and magnet ramping. To minimize the risk of either damage to the MR scanner or injury or death to humans as a result of a projectile incident, areas within and around the MR scanner are designed according to safety zones. A total of four zones (I, II, III, & IV) as defined by the ACR have been described and serve to demarcate and identify areas within and around the MR suite in terms of their respective safety risks and measures required to ensure safety of both staff and patients with detailed example zoning maps provided in the literature[41,42]. These zones increase in relative risk with Zone I being accessible to the general public (lowest risk of MR-related injury), Zone II is the interface region between publicly accessible (i.e., uncontrolled) Zone I and strictly controlled Zones III and IV. Zone III is the restricted area outside of the MR scanner in which free access by unscreened non-MR personnel may have adverse effects while Zone IV includes the MR scanner room and hence the highest safety risk area[42]. Each zone should be labelled with the appropriate level of access control with entry to Zone IV closed unless in use for patient care or maintenance and when open, the ACR recommends

using a "caution" barrier (e.g., adjusted straps or plastic chains) to inhibit unintended passage from Zone III to IV[43]. Following ACR guidelines[42], Zone III shall be physically restricted from general public access (i.e., badge swipe, key locks) where access is restricted to appropriately trained personnel as described in Section 4.2.

3.2 Fringe fields

All magnets have an associated static magnetic fringe field that decreases with increased distance from magnet isocenter based on the changing B_0 field. Vendor provided field maps (in units of mT/m) can be used to determine whether or not the scanner will interact with adjacent equipment that has set magnetic field limits (e.g., medical imaging systems, linear accelerators, etc.). Importantly, fringe fields exist in 3D space and may permeate through walls or floors. A diagnostic or MRI QMP with expertise in MRI siting should review the field location and extent in relation to the physical MR space, typically by importing MR scanner field maps provided by the manufacturer into the software used to design the MR suite and assess if additional magnetic shielding is required to reduce the fringe field at the time of construction. If shielding is required, shielding materials including low carbon content steel, silicone steel, or a high nickel content steel alloy (aka mu-metal) can be used to reduce the fringe field to within acceptable limits (often within the boundary of the MR scan room). Typically, these materials are installed by the same company that will install the RF shield and electrical penetration panels.

3.3 Common siting considerations

The MR scanner is a highly sensitive imaging system that requires specific siting requirements to be incorporated into the design and construction of the MR suite. Failure to meet these requirements can result in the presence of artifacts and subsequent degradation of image quality. Retrospective amelioration is often time consuming and may be expensive. Many of the major siting considerations have been discussed in detail in AAPM Report 20[44] (including vibration testing, nearby moving metal, cryogenic venting, powering, cooling by chillers, and city water changeover) with additional siting considerations unique to MR simulators operating in Radiation Oncology environments summarized in Table 2. The reader is also referred to the Planning Guide document provided by the scanner vendor for additional information pertaining to infrastructure requirements for magnet siting. The MRI suite should be designed for direct observation of the patient via an RF-shielded window and MR-safe cameras should be installed, often at the rear end of the bore, to enable patient monitoring. Finally, it is also important to consider storage space for coils, QA equipment, and phantoms in the overall room design.

3.3.1 Penetrating the RF Shield

Penetration of the RF shield is achieved using RF filters and detuned waveguides[44]. Installation of both devices is performed by the RF shield manufacturer but should be reviewed by the medical physicist as

listed in Table 2. It is strongly recommended to plan for additional waveguides (either via a blank or oversized penetration panel) beyond those recommended by the scanner manufacturer to accommodate future equipment purchases or auxiliary equipment such as infusion pumps, power injector, motion phantoms, ELPS, or research equipment with waveguides placed at the level of or below the operator console and ensure their use does not create tripping hazards. Retrofitting of waveguides can be performed by trained maintenance staff or by the RF shield vendor although it is highly recommended to have waveguides installed at the console area at the time of room construction. Due to the additional equipment used in an MR simulator such as the ELPS, it is important that integrated equipment be assessed at time of room design. For example, when installation of ELPS lasers occurred in a retrofitted fashion, RF cage damage occurred, resulting in a reduction in SNR and requiring an institution to disable lasers during patient scanning[41]. For some configurations, the ELPS lasers may generate RF interference and thus must be powered down during MRI data acquisition, thus a power switch located in the MRI control room or magnet room is necessary.

3.3.2 Proximity to major equipment

The MR scanner has the potential to impact the performance of a variety of equipment outside of the MR suite. The medical physicist should consult siting documentation provided by the MR scanner manufacturer and the information provided by the manufacturers of other major therapy, imaging, or other equipment to determine if the scanner's fringe field could interact with equipment, including on adjacent floors. The pre-installation manual provided by the MR vendor will provide a list of non-MR equipment affected by the fringe magnetic field of the scanner as well as a maximum field value that the system(s) can safely operate within. For linacs, several MR manufacturers have provided fringe field limits ranging from 0.05 mT to 0.1 mT while CT-SIMs have similar fringe field limits of 0.1 mT. For example, a 1.5 T MRI-linac was sited and changes in beam symmetry as a function of gantry angle were found to be up to 4% thus requiring steering adjustment, although the interference depended on distance from magnet isocenter and linac manufacturer[45]. Considerations for nearby proton therapy equipment must be carefully evaluated as high sensitivity, particularly with respect to installations with time-varying magnetic fields during gantry rotation, has been reported[46]. Special handling is also necessary for magnet co-siting including minimum magnet-magnet distances, shimming with both magnets ramped up, and considerations for high performance imaging such as spectroscopy[47]. Therefore, the QMP must verify that the projected strength of the fringe field is within stated manufacturer limits for each medical device. If the limit is not met, both vendors should be consulted to determine potential solutions following principles provided by AAPM Report No. 20[44]. If necessary, third-party vendors can be consulted to map fringe fields in adjacent rooms containing sensitive equipment. In addition and in compliance with FDA regulations, the 5 Gauss line

should be identified and if outside of Zone IV, appropriate steps taken to prevent exposure by the general public to this and higher static field strengths[48].

3.3.3 Siting for workflow considerations

Consideration should be given to the integration of the system into the clinical workflow of the Radiation Oncology Department. Specific considerations should include but not be limited to:

- Location relative to CT-SIM
- Location relative to treatment rooms and/or ancillary suites (i.e. intra-operative or brachytherapy)
- Availability of medical gases in the MR scan room and induction area (e.g. Zone III) and physical space for the anesthesia system, which is often MR conditional, if MR scanning under anesthesia is to be performed (e.g. for pediatric patients)
- Location relative to immobilization fabrication rooms

Siting an MR simulator in a geographically remote satellite location poses unique challenges in terms of overall workflow, patient access/utilization, and safety. As such, the MR simulator should be considered an integral part of the simulation process and should be sited as close as possible to resources that are part of this process.

4. MR SAFETY CONSIDERATIONS SPECIFIC TO RADIATION ONCOLOGY

4.1 General safety

A common misconception is that because MR imaging does not involve the use of ionizing radiation, the associated risks are therefore minimal. However, the MR environment poses unique risks to both patients and staff that have resulted in injury and deaths[49]. Table 3 outlines the major safety risks associated with MR scanning related to the major subsystems of the scanner, the associated limits to ensure safe operation of these devices, and the regulatory agencies.

4.2 MR Safety Program

In addition to operational limits imposed by regulatory agencies outlined in Table 3, the ACR has published the current standard of practice regarding MR safety within the MR community and it is strongly encouraged to implement the major recommendations. It is also recommended for Radiation Oncology Departments to work closely with their Diagnostic Radiology colleagues to develop and implement their MR safety program.

1. *Establish, implement and maintain MR safety policies and procedures* - Each site must have an MR safety committee to establish and implement MR safety policies and procedures. The committee should ideally be chaired by the MR medical director who provides final approval of the MR safety

committee guidelines. The committee should include representatives from groups that have direct interaction with the MR-SIM program (e.g., MR Technologists, radiation therapists, radiation oncologists, radiologists, RT/MRI physicists, nurses, and administrators) and is the front line in terms of establishing and enforcing MR safety policy.

2. *MR personnel and non-MR personnel* – access to Zones III and IV is granted following demonstration of MR safety competency with these areas restricted from general public access. Two main classifications of personnel are defined as non-MR (i.e., those who have no formal MRI training) or MR personnel (Level 1 and Level 2) based on their level of training and expertise. Level 1 Personnel have conducted basic MR safety training (initially and annually, typically via safety lectures) and can ensure their own safety in Zone III[42]. For Radiation Oncology Departments, the majority of the staff entering the MR suite will be considered Level 1 MR personnel and have demonstrated a basic understanding of the risks associated with the MR scanner. By contrast, Level 2 personnel includes those who have more extensive MR safety training including management of thermal burns, neuromuscular excitation, SAR, and conducting MR safety screening. Importantly, Level 2 personnel are required to accompany and supervise non-MR personnel while in Zone III or IV restricted areas[42]. The responsibility of Level 2 personnel is particularly important in a hybrid environment where the Radiation Oncology personnel may not be as knowledgeable as in standard diagnostic environments. Only MR personnel shall be provided free access to the secured Zone III via a physically restricting method (i.e., badge swipe, key access)[42].
3. *Screening for implanted medical devices (passive and active) and foreign metal* –In an MR environment, implantable medical devices pose risks including device malfunction resulting from damage to the device electronics by RF, dB/dt, or B_0 exposure, displacement and torque of the device due to the presence of ferrous and nonferrous metal components, respectively, and heating, particularly for those devices with long electrically conducting components such as lead wires, and when appropriate precautions have not been taken, have resulted in several deaths[50]. In addition, the presence of foreign metal such as bullet fragments, shrapnel, and metal filing, particularly in and around the eyes poses safety risks to the patient by either torque or displacement of the metal. For both active and passive implanted medical devices, manufacturers typically provide scanning guidelines. Several non-profit (e.g. http://www.mrisafety.com) and for profit (e.g. http://www.magresource.com/) databases exist that contain safety information. In many instances, the decision to image or not image a patient is made on a per-patient basis. To assist in this effort, it is recommended that the MR safety committee create and maintain guidelines for scanning

patients under a variety of conditions (anesthesia, claustrophobia) and types of devices (cardiac pacemakers, neural stimulators, pumps, shunts, etc.).

4. *MR safety screening form* – All patients are required to complete an MR screening form to identify the presence of implanted devices or foreign objects. An initial MR Screening can determine patient eligibility for MRI based on contraindications, such as extreme claustrophobia. Many manufacturers classify devices as MR Conditional[42], meaning that the device can be safely scanned under specific imaging conditions. Note that a designation of MR Conditional does not ensure that patients can be imaged at all field strengths (e.g. 1.5 T and 3.0 T). It is the responsibility of the MR staff and specifically the MR physicist to determine under what conditions these devices and the patient can be safely imaged. Examples of MRI screening forms can be found online at www.mrisafety.com, in the MR safety section of the ACR website, or in the ACR Guidance Document on MR Safe Practices[42].

   In many institutions, a nurse or scheduler may conduct the initial MR patient safety screening to ensure patient eligibility. The ACR currently recommends that nonemergent patients, such as those expected in an MR-SIM environment, be MR safety screened at least twice prior to being granted access to the MR environment with at least 1 of the screens performed by Level 2 MR Personnel verbally and/or interactively before entrance to Zone III[51].

5. *Ferrous and non-ferrous metal detectors* – Ambulatory, pediatric, sedated or cognitively impaired patients may not be able to accurately complete an MR screening form. Under these conditions, or when the presence of a foreign body is known but its composition is not known, ferrous metal detectors may be used to assist in the screening process. While not mandatory, several accrediting bodies within the US (The Joint Commission and ACR) recommend provisioning for these devices.

6. *MR safety equipment evaluation* – Per ACR recommendations[42], all objects (i.e., medical equipment, immobilization devices, patient monitoring devices, emergency response equipment, crash and anesthesia carts, patient transport such as wheelchairs, patient stretchers, etc.) being considered for introduction to Zone II should be tested with a strong handheld magnet (≥1,000 Gauss) and/or a handheld ferromagnetic detection device before entry to Zone III. Test results (including date, time, testing results, and methodology of clearance) shall be documented and used as needed for reference for future uses of the same equipment. All objects shall be affixed with labels using standard FDA labeling criteria for "MR safe" (wholly non-metallic objects), "MR-conditional," and "MR unsafe" materials following guidelines outlined in Kanal *et al*.[42] All references to previously used designations such as MR compatible should be replaced with the "MR safe," "MR-conditional," and "MR unsafe" terms. In addition, it is recommended that information from the manufacturer be sought to confirm the current MR safety status of a given

device. The majority of manufacturers provide up-to-date listings of the status of their devices through their websites. It is important to note that some vacuum formed devices have been known to include MR unsafe components such as ferrous valves or pumps. While these devices may not pose a risk of projectile injury due to their size and encapsulation, they can degrade image quality if located close to the patient's anatomy. Thermoplastic devices which involve the use of water baths should be completely dry before placement on the patient in the MR simulator in order to reduce the risk of heating and potential patient burns.

7. *Gadolinium Based Contrast Agents (GBCAs)* – Exogenous gadolinium chelated contrast agents are routinely administered in Diagnostic Radiology and during MR-SIM. Gadolinium is paramagnetic and works to shorten both T1 and T2 relaxation times. For most anatomical imaging, T1 shortening dominates, leading to signal enhancement on T1-weighted images. It was originally thought that GBCAs were completely excreted by the renal system. However, mounting evidence suggests that gadolinium can dissociate from its chelating agent in vivo, leading to accumulation and retention of free gadolinium in tissues such as brain, bone, skin, and liver[52,53]. It is generally accepted that use of non-ionic, macrocyclic GBCAs results in the lowest deposition of free gadolinium[53]. Another concern with GBCAs is development of nephrogenic systemic fibrosis (NSF) in patients with severely compromised renal function. Fortunately, changes in clinical practice of using GBCAs in patients with impaired renal function have essentially eradicated the incidence of NSF[52]. The MR safety committee should establish guidelines regarding (1) which gadolinium agent will be utilized for MR-SIM, (2) what dose levels will be administered with consideration of best clinical practices, and (3) management in patients with compromised renal function, all following guidance recommended by the ACR[54].
8. *Establishment of emergency preparedness procedures* – Per ACR guidelines[42], in the event of a patient emergency, MR safety protocols including restricting access and screening of responders or equipment (i.e., fire extinguishers, stretchers) must be handled by Level 2 personnel. Patients requiring emergency medical attention must be immediately removed from Zone IV to a pre-defined MR safe location before initiating medical care. Detailed guidelines for MR facility emergency preparedness (including fire and electrical hazards) are provided in the ACR Guidance Document on MR Safe Practices[42]. Per ACR recommendations, MRI facilities must have clearly marked, readily accessible MR Conditional or MR Safe fire extinguishing equipment physically stored within Zones III or IV with conventional fire extinguishers not verified as safe in an MR environment should be restricted from Zone III[51]. Mock code training should be performed annually

to ensure staff members understand their roles and responsibilities with respect to the MRI environment.

9. *Patient-specific MR safety evaluation* - Appendix A provides an example MR Sim Patient QA Checklist that can be used before each patient's MRI procedure to ensure patient safety and workflow are followed and properly documented. The final scan/no-scan decision should be an individual patient risk/benefit decision made by an attending physician (radiologist or radiation oncologist) with Level 2 MR safety training and in consultation with the patient. If other involved MRI technologists, radiation therapists, physicians, or medical physicists feel the safety of the patient is at risk, all staff shall have the option to halt the imaging procedure. If the issue cannot be resolved with the responsible physician, the MR Medical Director or their designate shall make the final decision regarding whether to proceed with the scan.

5. MR SIMULATOR STAFFING AND TRAINING OVERVIEW

5.1 MR personnel and staffing

As previously described, two main classifications of personnel are defined as non-MR (i.e., those who have no formal training) or MR (Level 1 and Level 2). Typical examples of Level 1 personnel include radiation oncologists, therapy medical physicists, Radiation Oncology nursing staff, radiation therapists, and researchers. Level 2 personnel typically involve staff who have direct involvement with scanning of patients (i.e. MR technologists, MR-trained radiation therapists) and technical staff (diagnostic and therapy physicists, service engineers). Per ACR recommendations, each institution's MR medical director (typically a Radiologist) is responsible for determining the necessary training to qualify as Level 2 MR personnel. Training must be completed on an annual basis. It is recommended that at least one Radiation Oncologist meets the Level 2 personnel criteria in the MR-SIM program.

It should be emphasized that Level 2 personnel carry a great responsibility of conducting MR safety screening and ensuring the safety of non-MR and Level 1 personnel in Zones III and IV. Therefore, it is critical to implement an MR safety training program while having cross-trained staff develop a high level of comfort with MRI. The siting of an MR scanner outside of Diagnostic Radiology (i.e. Radiation Oncology) introduces unique challenges to ensuring MR safety given the significantly larger pool of untrained personnel. Hence, we recommend that extra effort be made to educate all staff within the vicinity of the MR suite regardless of being designated as MR personnel. Based on the TG members' collective experience, the authors of this TG recommend a minimum of 2 working months (320 contact hours) in an MRI environment for cross-trained staff from Radiation Oncology to be given the responsibility of Level 2 personnel. It is strongly recommended that MR Safety competencies are demonstrated to qualified Level

2 personnel, including patient screening, understanding of emergency procedures, investigating implants for make and model, and monitoring control over Zone IV. This recommendation assumes that complex clinical situations such as clearing implants with unknown makes and models, active implants (i.e., loop recorders, deep brain stimulators, pacemakers, pain pumps, etc.) or patients with metal fragments/implants in or near the eye will be handled by a Level 2 designated MR radiologist, the MR medical director, or a specifically designated Level 2 MR personnel following criteria for acceptability predetermined by the medical director[42].

5.2 Operational models

Due to the need for both diagnostic and therapy expertise, a multi-disciplinary MR-SIM team is essential for initial and ongoing operation of the MR-SIM program. Table 4 presents two major operational models (traditional and specialized) and the advantages/disadvantages of each, although hybrid models may also be considered. For both operational models, it is recommended that a subset of dedicated staff is used for the MR-SIM program to ensure continuity and to avoid loss of expertise due to time gaps in coverage. For certified radiation therapists, the current requirements to obtain ARRT certification in MRI via the post-primary pathway include completion of the MRI Clinical Experience Requirements (MR safety training and completion of 125 procedures or as specified by ARRT). Another example of a specialized model that has emerged includes cross-training MR technologists in the immobilization and setup of patients using external lasers for treatment delivery purposes. This can be accomplished via observations in CT-SIM, treatment planning, and treatment delivery and through demonstrated competencies. Furthermore, the selection of the appropriate sequences for RTP purposes must be emphasized during practical training.

5.3 Training recommendations

Regardless of staffing model, it is important to cross-train both MR technologists and radiation therapists to understand both simulation and MR scanning processes. MR technologists and radiologists must understand the importance of patient positioning and how scan quality may be affected by the presence of immobilization devices, immobilization material, and RT-specific scanning parameters. Similarly, it is absolutely critical that all staff members are adequately trained in MR safety. It is recommended that key personnel in the MR-SIM program undergo formal didactic MR safety training offered by the community (e.g. American Board of Magnetic Resonance Safety http://abmrs.org/). Contact hours for MR safety training can be obtained via personnel observations in Diagnostic Radiology including patient positioning (for example, forming no conductive loops, preventing skin folds), performing QA tests, and MRI safety screening. To document clinical competency, logs should be maintained of procedures observed, including documentation of the Level 2 personnel who supervised the tasks.

During the initial stages (i.e., first few months) of MR-SIM program implementation, most vendors provide applications training that typically includes basic training on protocol optimization. This time is crucial for developing disease site-specific image acquisition protocols, optimizing resolution and contrast while minimizing exam time, scanning in the presence of immobilization devices with RT patient positioning, and is beneficial for both diagnostic and therapy physicists involved in the MR-SIM program. It is recommended that radiologists are involved in, at a minimum, the initial stages of the MR-SIM program to provide image quality feedback for different disease sites. Many vendors also provide basic didactic training on MRI fundamentals and scanning protocols specific to the equipment being implemented that can be built upon during initial MR-SIM implementation. Diagnostic physicists covering an MR-SIM program will also require training on the use of MR simulator equipment such as the flat table top, lasers, distortion assessment phantoms, and overall clinical training in immobilization devices and patient positioning. Thus, collaborative training initiatives are critical to the success of an MR-SIM program, especially in the initial phase of the program. Table 5 outlines common members of the MR-SIM team, the full time effort (FTE), and potential roles for each team member assuming the Traditional Operational Model is followed based on consensus of several early adopters in MR-SIM in a variety of clinical settings. The initial FTE defined in Table 5 may be extended or reduced based on in-house expertise, comfort level/prior experience with MRI, implementing new indications, and case complexity. Note that additional support may be provided by an anesthesiology team and administrators that are not included in the table.

6. RECOMMENDED QA FOR MR SIMULATORS

Beyond general QA for MRI, RT-specific QA tasks and tolerances are defined to ensure high spatial accuracy, image integrity, and repeatability of MR-SIM exams. QA shall be performed by QMPs at the acceptance and commissioning stage, either independently or with vendor support, to characterize system performance and establish baseline results for future periodic QA. To ensure ongoing system performance following MR simulator commissioning, it is necessary to establish and maintain a robust Quality Assurance Program. Appendix B outlines a consensus Monthly QA program developed by the TG members including suggested tolerances. It is important to note that for shared MRI scanners between Diagnostic Radiology and Radiation Oncology, the scanner may be accredited by a diagnostic accreditation agency such as the ACR and thus may require differing QA guidelines. In this scenario, routine QA protocols involving the scanning of a quality control phantom should be followed as described by the certifying body (for example, scanning the ACR quality control test protocol performed weekly as required for ACR certification). The QA program outlined here is derived from the following: cited standards in MRI relevant to MR simulators and MR-SIM, translation of limits from other well-established AAPM TGs

with references provided, and consensus among TG members' QA programs. TG members span a variety of institutions, vendor platforms, field strengths (1.0 T to 3.0 T) and practice settings (academic centers and satellite/community settings) thus it is our expectation that this QA program will be applicable to the broader community.

6.1 Initial MR simulator equipment evaluation

During and after installation, an initial MR equipment evaluation and acceptance testing by a QMP in conjunction with the vendor shall be performed as outlined in AAPM Report No. 100 (MR Subcommittee TG 1)[55]. Testing of radiofrequency shielding is necessary once the MR scanner is installed and the RF shielding of the room is complete to ensure the RF cage integrity has been maintained using methods outlined in AAPM Report No. 100[55]. It is important for the QMP to ensure that vendor-provided specifications of large FOV "empty" (i.e., no patient or object in the bore) magnetic field homogeneity and gradient non-linearity be verified during this period as outlined in subsequent sections. The installation of ELPS lasers resulted in RF cage damage, leading to RF interference, artifacts during scanning, and an SNR reduction of 5-13% occurred when ELPS lasers were left powered on during MR-SIM, thus requiring the disabling of the ELPS lasers during MR imaging[41]. A magnetic field drift test shall be performed during acceptance testing and assessed during the first two months of operation and RF subsystem tests to ensure the transmit frequency (center frequency) and transmit gain shall be conducted as outlined in Table 6 and in AAPM Report No. 100[55].

6.2 Commissioning, annual testing, and QA post-software and hardware changes

Commissioning of the MR simulator is required to ensure that the system meets accepted quality standards and to establish baseline measurement values/tolerances as outlined in Table 6 with detailed references provided in the table describing how to conduct the test. In addition, establishing baselines for the monthly and daily QA programs described in section 7 must also be conducted at commissioning. All commissioning, annual testing, and QA that occurs post-software and hardware changes shall be conducted by a QMP.

6.2.1 Characterization of B_0 homogeneities

Magnetic field homogeneity (MFH, or B_0 inhomogeneity) is defined as the magnetic field variation over a certain DSV expressed in part per million (ppm) of the static magnetic field value or equivalent resonant frequency (Hz)[55,56]. MFH can be affected by internal effects (inaccuracies in coil windings or passive shim coils) or external effects (perturbations induced by ferromagnetic structures near magnet). Inhomogeneities may impact image uniformity, contribute to geometrical distortion, chemical shift, poor fat saturation, and loss of SNR. At the installation stage, the vendor's service personnel maximize MFH through a process called shimming. Depending on the MR simulator design, shimming can be performed either passively by placing small pieces of iron or steel in strategic positions, or actively by modifying current in a set of shimming coils placed inside the scanner bore. Shimming of the MR scanner requires specialized training, specialty equipment (i.e., large FOV field cameras), specialized analysis software, and machine access that are typically only available to the vendor's service personnel. Even though it is not a procedure that can be performed independently by QMPs, a QMP shall verify that the magnet shim results meet the vendor's specifications. It is highly recommended that medical physicists keep a copy of the magnet shim results for future reference.

Immediately after MR simulator installation, a QMP should independently characterize MFH using a large (>35 cm diameter) homogeneous spherical phantom that is often provided by the vendor. The phantom should be allowed to equilibrate to room temperature in the scanner for ~30 minutes prior to imaging. AAPM Report 100[55] and the updated ACR Quality Control Manual on MRI[57] provide detailed methods that are commonly used to measure MFH: spectral peak, bandwidth difference, phase map, and phase difference mapping yielding results in units of parts per million (ppm)[55]. While more complex, it is strongly recommended that the phase difference mapping technique is used as it provides a voxel-wise based methodology for assessing trends in MFH in multiple planes. Spectral peak and bandwidth difference provide only global evaluation via a single reported metric[57] and the single phase mapping technique yields an upper bound measurement of B_0 inhomogeneity.

To conduct phase difference mapping, two or more phase images are acquired using a gradient echo (GRE) sequence at two echo times (TEs, listed as TE_2 and TE_1 in Equation 1) that are separated by a few milliseconds. This can be achieved using either a dual echo GRE sequence, or a regular GRE sequence scanned twice at two different TEs. For the latter, it is crucial to make sure that the transmitter and receiver gains do not change between the two scans. To conduct this test, the QMP must enable the saving of both magnitude and phase MRI data on the MRI scanner console. If phase wraps (i.e., artificial jumps in signal near boundaries) are observed during review of the phase images, the images must first be unwrapped until the original, smoothed phase is recovered before further processing. Phase unwrapping can be conducted

using well-known freeware versions such as Prelude[58] in FSL (Analysis Group, FMRIB, Oxford, UK[59-61]) that typically minimizes the sum of squared phase difference between voxels along the interfaces of the wrapped regions. Phase subtraction should then be conducted and the final MFH can be calculated on a voxel-by-voxel basis using Eq. 1[62]:

$$\Delta B_0\,(ppm) = \frac{\varphi_{TE_2} - \varphi_{TE_1}}{\gamma(TE_2 - TE_1)} \quad (1)$$

where φ represents the unwrapped phase at a location in image at respective echo times, TE_1 and TE_2. MFH is typically reported using peak-to-peak and/or root-mean-square values over a selected region of interest (typically the phantom volume) with limits outlined in Table 6. This value shall also be within the vendor specification that may be defined across a certain DSV. A comprehensive report has outlined B_0 homogeneity specifications across a 40 cm DSV ranging from 0.35 to 5 ppm (median = 0.75 ppm) VRMS for 1.5 T systems and 0.2 to 1.4 ppm (median = 0.5 ppm) VRMS for 3 T systems[63]. Detailed methods for measuring MFH are outlined in several other reports[57,63].

6.2.2 Characterization of residual GNL-induced distortions

The gradient field introduces small spatially linear variations in the main magnetic field in a predictable pattern and encodes spatial information into MR signal, which is then used to reconstruct MR images. Thus, the accuracy of spatial mapping relies on the linearity of the gradient system, which is magnet-specific. Imperfections in gradient linearity can result in inaccurate spatial mapping and therefore cause geometric distortion. Modern MRI vendors incorporate algorithms to correct raw MRI data for known gradient nonlinearities in their gradient coil designs. However, it has been shown that even after vendor-supplied GNL 3D distortion corrections have been applied, residual distortions are >1 mm at radii >10 cm from magnet isocenter and have a tendency to be worse for open-bore MR simulator units as compared to cylindrical bores[64-66]. Residual post-correction distortion for the cylindrical bore magnets increases gradually with increasing distance from magnet isocenter, with maximum distortions (near 20 cm from isocenter) of 2 to 3 mm[64,66,67]. Thus, assessment of residual GNL distortions (i.e., after vendor-provided 3D corrections are enabled) as a function of FOV must be conducted with a large FOV phantom (>80% of the useable FOV) as outlined in Table 6. The recommendation of employing 3D GNL correction is best summarized in Figure 2 highlighting the residual distortions that exist even after 2D GNL correction have been enabled. Note the loss of geometric fidelity with distance from isocenter for the grid phantom.

Several phantom-based methods have been developed for measurement and correction of GNL effects[67-70]. The recommended approach for evaluating GNL distortions is to use the reverse gradient

technique[71]. Here, a 3D GRE image is acquired with vendor-supplied 3D corrections enabled[62,71,72] and the same scan repeated using opposite readout gradient polarities along each axes: LR/RL, AP/PA, and SI/IS. B_0 field inhomogeneities appear to shift when the polarity of the read gradient is reversed, while gradient distortions will remain constant. Therefore, the distortion due to GNL can be isolated by taking the average distortion of the two scans. While most MRI scanners offer the option of changing the polarity in the clinical interface, some may require access to research or service mode to enable this functionality.

To analyze GNL, the large FOV phantom landmarks may be registered to a binary template[73,74] or a CT of the phantom[64,67]. In-house software is commonly used for control point detection and to calculate the distortion as the difference of the measured centroid positions from the known positions. GNL distortion maps should be assessed after major repairs and hardware/software upgrades and compared to baseline commissioning data. Vendor-supplied or third-party phantoms and analysis software are available for end users. If the GNL is found to be out of specification outlined in Table 6, the QMP should work with the vendor to address the accuracy of the spherical harmonics solution and work to improve the distortion across a large FOV. Recent work by Tao et al. found that using high-order terms up to the 10th order, root mean square error could be reduced from 0.7 mm (5th order) down to 0.36 mm for a compact, asymmetric MR gradient system used for brain imaging[75]. This suggests that introducing additional terms into the solution may offer further potential to reduce GNL to be within specification.

6.2.3 Effects of B1 inhomogeneities

In addition to spatial distortion, the intensities of MR images may be impacted by non-uniformity of the transmitted RF field (termed $B1^+$ non-uniformities) that arise from the shape of the subject, choice of RF coils and coil configurations, field strength, transmit performance, and pulse sequence selection[76]. The image intensity inhomogeneities may affect the accuracy and performance of intensity-based image segmentation and registration algorithms. However, for manual contouring, these effects are expected to be less critical. At present, it is important to understand the available options on the MR scanner during acquisition for reducing image intensity non-uniformities as described in Section 7.7.2 .

6.2.4 RF coil constancy parameters

Multi-channel phased-array RF coils are commonly employed during MR simulation due to their SNR and acceleration improvements along with the added benefit of accommodating patients immobilized in treatment position[33]. In an MR simulator environment, repeated flexing of the coils during patient setup to accommodate immobilization devices may introduce added strain to the coils, resulting in failure of one or more coil elements over time thereby necessitating the need for frequent testing. To address this need

and per ACR recommendations, a QMP shall establish baseline RF coil signal-to-noise ratio (SNR) and image intensity uniformity values and tolerances for both the final reconstructed image as well as images from individual coil elements. To establish RF coil testing protocols the reader is referred to the ACR RF coil testing guidelines[57].

For both SNR and uniformity measurements, the QMP should investigate whether or not vendor provided testing and analysis tools are available. These techniques are preferred given that they involve well characterized test phantoms, testing jigs, scanning protocols, and analysis tools. Within this context, it is recommended that MR scanner manufacturers provide easy access to these tools. In the absence of access to these, the QMP is encouraged to develop testing protocols that are consistent with National Electrical Manufacturers Association (NEMA) in standards MS 6-2008 and MS 9-2008. In-house protocols should include recommendations regarding specific phantoms, imaging sequences and instructions on appropriate and reproducible RF coil placement on the test phantom. Alternatively, the integrity of all elements can be assessed by acquiring a noise scan and calculating the noise co-variance matrix[77].

6.2.5 Characterization of motion estimation accuracy

Motion estimates obtained from cine MRI and/or respiratory-correlated 4D-MRI may be used to determine internal target volumes and planning risk volumes in a manner analogous with 4DCT[78,79]. Specifics of motion management techniques are described in detail in Section 8.6. During MR simulator commissioning, the accuracy of motion estimates obtained with these MR imaging techniques should be characterized. MRI-compatible programmable dynamic motion phantoms have recently become commercially available and offer advantages to characterize motion estimation accuracy[80], thus it is strongly recommended that MR-SIM programs purchase and implement this equipment for motion management QA. The phantoms are driven by computer systems that remain in the MRI control room with output signals interfaced via waveguides or filters installed in the RF penetration panel. As outlined by AAPM Task Group 76, dynamic phantoms should simulate human respiration, provide the necessary gating/feedback mechanism to facilitate acquisition, and have a high degree of reliability[81]. Commonly, the programmable phantoms support a wide array of motion waveforms, from basic sinusoidal to patient-specific waveforms obtained from respiratory surrogates (e.g., respiratory bellows, reflector-camera, etc.). The frequency, amplitude, and trajectory of phantom targets can be adjusted in the motion phantom software using clinically applicable parameters (i.e., excursion > 5 mm threshold for motion management[81]) and imaged using similar cine or 4D-MRI scan parameters as those used clinically. Motion estimates obtained from imaging should be compared against programmed phantom motion in accordance with Table 6.

6.3 Monthly QA

Table 7 outlines recommended monthly QA tests to be completed by or under the direct supervision[82] of a QMP. The estimated time to complete all tests is ~1 hour. Detailed descriptions for evaluations specific to MR simulators or major tests with associated references are also described.

6.3.1 Mechanical checks

6.3.1a Table motion

MR scan table position accuracy and indexing should be assessed. A simple method to test scan table position accuracy involves the use of a phantom with an MR identifiable fiducial that can be landmarked and moved to the magnet isocenter. Scanning the phantom using an imaging plane that bisects the fiducial allows for identification of the fiducial coordinates. Accurate indexing of the MR scan table should result in the center of the fiducial being at a superior/inferior or Z axis position within $\pm$ 1 mm of isocenter. This test can also be performed by movement of the table by a fixed distance from a given reference location. For sites with external laser systems, the intersection of the lasers can serve as this reference location. Table increment can also be tested in a similar way by movement of the table through a series of incremental distances (e.g., 10 mm increments) and an indexing accuracy of $\pm$ 1 mm should be achievable in a manner similar to CT-SIM[83].

6.3.1b Laser alignment and orthogonality

Mutic *et al*. have provided guidance on specific errors for laser alignment and include a spatial position accuracy of $\pm$ 2 mm[83]. Adapting for MR simulators, an additional magnet/laser isocenter coincidence of $\pm$ 2 mm is also recommended. While these tolerances provide minimum tolerances, with high precision laser localizer systems commercially available, a tolerance of $\pm$ 1 mm should be achievable for both tests. Needs specific to SRS should be obtained by consulting AAPM TG-117 currently under development that is focusing on this special use case.

6.3.2 MR image quality constancy

Assessment of MR image quality constancy (e.g., image uniformity, contrast, resolution, ghosting, etc.) is part of general QA for MRI. The user is referred to guidance documents such as AAPM Report 100[55], ACR MRI Quality Control Manual[56], and ACR Large Phantom Test Guidance for descriptions, action levels of each test, and recommending testing frequencies for both diagnostic MRI and MR simulators.

6.3.3 System spatial fidelity / geometric accuracy

System spatial fidelity (defined as the total distortion from all sources including B_0 inhomogeneity and GNL) should be assessed monthly and daily before use. Of note is that a full GNL assessment is to be conducted at commissioning and after major hardware/software changes to the MR simulator, thus routine

(monthly/daily) total distortion assessment is meant to serve as a constancy check. It is recommended that distortion is evaluated using a large phantom (>30 cm in diameter or width) with known landmarks centered at scanner isocenter or alternatively, a planar phantom oriented in three cardinal planes[32]. While distortions of ± 1 mm have been described at distances <10 cm from isocenter, a tolerance of ≤ 2 mm across 25 cm FOV with GNL corrections enabled should be achievable based on TG member experience and reported literature across several vendors[64,66,71]. If the total distortion is > 2 mm at distances <25 cm from magnet isocenter, the QMP should consult with the vendor to resolve as described in 6.2.2. Consideration should also be made for use case, such as the more rigorous requirements for SRS and MR-only treatment planning workflows that are currently under development. MR simulator vendors often provide phantoms and distortion assessment tools to ease routine total distortion analysis. In addition, third-party vendor solutions are also becoming more readily available.

6.3.4 Flexible RF coil testing

While rigid RF coils are typically used less frequently in an MR-SIM setting, their rigid design also ensures that they are less susceptible to physical damage and thus it is recommended they undergo routine testing as part of quarterly and annual testing unless functionality is limited or an artifact is observed on imaging. As noted previously, flexible RF coils may undergo significant strain during simulation resulting in coil element failures that can degrade image quality via artifacts, the loss of uniformity[84], and decreased SNR. However, global SNR and uniformity measurements are often not sensitive to a single element's performance, thus it is recommended that monthly testing of the individual elements of flexible array coils be performed to ensure functionality and that individual elements are within tolerances established either by the vendor or QMP at the time of commissioning as described in Section 6.2.4. Many vendors provide evaluation tools or a noise scan can be acquired and a noise co-variance matrix can be evaluated[77].

6.4 Daily QA

Table 8 highlights key safety, mechanical, and imaging components for a daily MR simulator QA program. Daily QA may be conducted by an MRI technologist or a cross-trained radiation therapist who has met the minimum training criteria outlined in Section 5.3 with oversight by a QMP. The estimated time to conduct daily QA is ≤ 30 minutes including scanning time.

6.4.1 Checking for the presence of foreign metal

B_0 homogeneity and hence image quality can be compromised by the presence of small amounts of ferrous and other metals such as hair clips, paper clips, and small pieces of metal that have inadvertently become affixed to the bore. It is recommended that daily visual inspection of the MR scanner bore for the presence of foreign metal objects should be performed by the MR technologist. Scanning a large volume phantom using a GRE based sequence with a low bandwidth will increase the sensitivity of the sequence to susceptibility induced distortion from the metal and allow localization of the object within the bore for removal. Removal of lodged objects within the bore or MRI covers should be conducted by qualified MR field service engineers either employed by the institution supporting the equipment or by the vendor.

7. RECOMMENDATIONS FOR OPTIMIZATION OF RT-SPECIFIC MR WORKFLOWS

7.1 MR-SIM clinical workflow process map

In the conventional simulation workflow, CT-SIM precedes MR-SIM. In what is termed the "reversed simulation workflow," MR-SIM precedes the CT-SIM as shown via the process trees in Figure 3. Note that processes outlined in red denote additional steps that may differ from a conventional CT-only workflow but are necessary to ensure compatibility with MR simulator equipment and high quality MR imaging. Also note that the CT imaging in the reversed simulation workflow does not necessarily need to be performed on a CT-SIM. In addition, special consideration should be given to the administration of GBCAs in the reversed simulation workflow since the presence of GBCAs may affect Hounsfield values obtained during CT-SIM.

7.2. Setup reference markers and isocenter placement

Most MR simulator software packages do not currently allow for interactive absolute isocenter marking using patient images, thus most end users use their treatment planning system or a third-party contouring software to define isocenter for MR-SIM[32,85]. Until absolute isocenter marking is available, it is recommended that MR-safe fiducial markers be placed on the skin tattoos so that the reference marks can be visualized on MR to assist in localizing isocenter on the images.

7.3. Patient positioning, immobilization device construction, and coil configurations

The ACR highly recommends the use of MR-Safe gowns due to recent reports of clothing incorporating ferromagnetic and/or conductive materials (e.g., antimicrobial silver and copper) causing thermal injury and/or burns[43]. Shoes shall be removed to prevent ferrous sediment from entering the bore and jewelry shall be removed to minimize the risk of RF and gradient heating.

Similar to CT-SIM, most MR-SIM scanning is performed in the head-first-supine patient positioning with some exceptions such as breast, extremities and rectal cases. Table 9 summarizes example

coil configurations and immobilization devices for various disease sites. Immobilization devices such as alpha cradles and vacuum cushions must fit within the MR simulator bore. In institutions where the CT-SIM and MR simulator bore sizes differ, it is recommended that a template be built of the MR simulator bore or coils to establish maximum size constraints and clearance of the immobilization devices[33]. Coils are often placed after positioning and immobilization. Some scanners are equipped with appropriate holders for using flexible RF coils around the immobilization mask (e.g., brain and head and neck) to expedite patient setup. For other areas, Velcro straps are often used to affix the coil elements close to the patient's surface. Wrapping the coils close to the patient improves the SNR and image intensity uniformity, which may have important implications for intensity-based tasks in RT such as auto-segmentation and deformable image registration[85]. Ideally, target volumes for MR-SIM should be centered in the bore to minimize gradient non-linearity distortions, maximize field homogeneity, and to allocate room for RF coil placement. In the case of lateral targets (i.e., breast) or extremities, uncertainty arising from GNL distortions as described in section 6.2.2 shall be considered. In cases of large body habitus or with close proximity between the patient and bore surface, caution must be exercised to ensure adequate (~1 cm or greater thickness) nonconducting padding is used at contact points[86].

MR-compatible immobilization devices can be custom-built in-house or purchased through third-party vendors who offer an increasing assortment of MR-compatible immobilization devices. Ideally, immobilization material would be "MR-optimal" and not just MR-compatible—meaning that the material should not introduce unnecessary susceptibility artifacts, produce an undesired signal, or increase the safety profile/risk, and it should be compatible with RF coil systems used for signal reception. Carbon fiber immobilization devices will need to be refabricated from MR-optimal material (such as melamine) for use during MR-SIM[33]. Carbon fiber is electrically conductive and may interfere with the RF field when used in the MR scanner, yielding a reduction in SNR and uniformity[87] as well as a risk of thermal injury to the patient, thus should be avoided.

7.4 Acquisition considerations

Determination of the true 3D extent of disease and its proximity to adjacent OAR is central to RT treatment planning. General optimization of MRI protocols involves maximizing spatial resolution and tissue contrast while minimizing total acquisition time[88,89]. Beyond these considerations, radiotherapy-specific MRI protocol optimization involves a) minimization of distortions and image intensity non-uniformities (IINU), b) ensuring sufficient landmarks exist for co-registration to CT, and c) maintaining anatomical congruence in the presence of motion. The following subsections provide recommendations for RT-specific MRI protocol optimization. In addition, the reader is referred to Appendix C, which contains sample vendor-neutral MR simulation imaging protocols for several body regions.

7.4.1 Mitigation of geometric distortion

Distortions in MRI have been well characterized and the reader is referred to the literature for additional background information[3-11]. Distortions arise from (1) inhomogeneity of the static magnetic field, (2) nonlinearity of the magnetic field gradients, and (3) the susceptibility distribution of the patient being imaged[4]. The severity of the first two sources of distortion increases with radial distance from the MRI isocenter[12,13]. The severity of susceptibility distortion increases with magnetic field strength and at discontinuities of magnetic susceptibility (e.g., air-tissue and tissue-metal interfaces)[11,12]. It has been shown that static field inhomogeneity, magnetic susceptibility, and chemical shift distortions can be reduced by increasing gradient strength (i.e., increasing readout bandwidth), while gradient nonlinearity errors are independent of gradient strength[4]. The goal of the strategy discussed below is distortion mitigation during image acquisition; distortion correction is more complicated and requires additional tools not generally available at the time of this writing (see Unmet Needs and Future Directions section).

7.4.1a Optimized pulse sequences

The majority of pulse sequences used for clinical scanning are spin warp sequences, in which one line of k-space is acquired per repetition time (TR). These sequences generally fall into two categories: spin-echo and gradient-echo (GRE). Spin echo-based pulse sequences intrinsically correct for B_0 inhomogeneities by applying an additional 180 degree refocusing pulse. Therefore, spin-echo pulse sequences are more robust against signal dropout in regions of high magnetic susceptibility gradients than GRE-based sequences and are preferred for MR-SIM[90]. However, GRE sequences may be desirable for some applications due to their faster acquisition times (assuming short echo times e.g., T_1-weighted MRI) versus spin echoes, as described in Section 7.6.1

7.4.1b Optimization of B_0 field homogeneity

B_0 inhomogeneities arising from the patient can be reduced through a process called active shimming. In this process, the system performs an optimization to adjust currents applied to a separate set of active shim coils positioned along the magnet bore over a prescribed volume of interest. Active shimming is dependent on the patient and prescribed volume of interest, and, thus, should be performed for each MR-SIM exam to further optimize B_0 homogeneity beyond the superconducting (if applicable) and passive shimming performed on the empty magnet during scanner installation. Field homogeneity also depends upon the magnet design and the initial siting of the equipment. Higher field strength systems typically offer finer control through the use of higher-order shims. Geometric distortions can be reduced and fat suppression efficacy improved through the use of patient-specific active shimming. Generally speaking, the resonant frequency (f0) of the scanner is often assumed to be constant over the entire imaging

acquisition session although scanner resonant frequencies may change due to temperature changes, warming of electronics, or variations in the subject composition (i.e. presence of air, tissue, etc.) in or near the patient or object volume used for f0 determination[91]. For example, in a study of nine pelvic cases on a 1.0 T scanner, a maximum f0 shift of 16 Hz (corresponding to 0.12 mm using the T2 scan parameters) occurred over ~50 minutes[92]. Thus, care should be taken to ensure that high-order shim currents are held constant throughout the entire MR-SIM exam by eliminating preparatory scans, maintaining consistent FOV and RF coil configurations, etc.

7.4.1c Optimization of readout bandwidth

For conventional spin warp pulse sequences, distortions due to static field inhomogeneity, magnetic susceptibility, and chemical shift occur along the readout direction. The severity of the distortions can be reduced by increasing the readout bandwidth at the expense of SNR. A general rule of thumb to mitigate distortions is to set the readout bandwidth to twice the fat-water shift (e.g., 440 Hz at 1.5 T and 880 Hz at 3 T)[90]. While this approach is effective at mitigating distortion, it also reduces SNR by at least 30%.

A guiding approach that minimizes SNR loss is presented here. This method is based on simulations of magnetic field distortions induced by local magnetic susceptibility differences[93]. First, a permissible shift along the readout direction must be established. The permissible shift will depend on the type of treatment prescribed (i.e., stereotactic or non-stereotactic) and the imaging workflow (i.e., CT+MR as described in this TG, or MR-only which may be more prevalent in the future). Second, the maximum magnitude of the magnetic field distortions for the specific body region being imaged is required (range 2.48-5.66 ppm)[93]. Then, the readout bandwidth (BW) required to reduce geometric distortions to permissible ranges is obtained using the following equation:

$$Readout\ BW\left(\frac{Hz}{pixel}\right) = \frac{Max\ \Delta B_0(ppm) * f_0(MHz) * Readout\ FOV\ (mm)}{Permissible\ Shift\ Along\ Readout\ (mm) * Readout\ Matrix\ Size} \qquad (2)$$

where f_0 is the system frequency, and Readout FOV and Readout Matrix Size are desired FOV and matrix sizes, respectively, that govern spatial coverage and resolution. This approach tailors the readout bandwidth setting for a specific scanning protocol, field strength, and body region while preventing excessive loss in SNR. It should be noted that the upper limit on readout bandwidth may be limited by the available gradient system on the scanner. In addition, the lower limit on readout bandwidth is the value that minimizes chemical shift (i.e., water-fat shift) to less than 1 pixel for a particular field strength (e.g., 220 Hz at 1.5 T and 440 Hz at 3 T).

Once the readout bandwidth has been optimized for a specific disease site, several strategies can be employed to recover lost SNR. One approach is to increase the number of averages (excitations). If the number of averages is increased by N, this method will increase the acquisition time by a factor of N, but will only increase SNR by the square root of N. Alternative approaches include switching to 3D acquisitions and utilizing phase and slice oversampling, noting that each of these strategies will result in increased scan times. Increasing the partial Fourier fraction and reducing the parallel imaging acceleration factor are additional ways of increasing SNR[94].

7.5. Optimization to reduce gradient nonlinearity-induced distortions

The severity of GNL distortion increases with radial distance from isocenter, making target volumes requiring large fields of view (e.g., supine breast, extremity sarcomas, and spine) most vulnerable. Gradient nonlinearities can be reduced by ensuring that the center of the prescribed imaging volume is shifted to the MR scanner isocenter along the superior-inferior direction before the acquisition begins[14,20] or laterally in MR simulator configurations that allow lateral couch translation[32]. This process effectively forces the prescribed imaging volume over the region of highest gradient linearity in this direction.

For tumor sites requiring large superior-inferior (S-I) scan coverage (e.g., spine and extremity soft tissue sarcoma), the severity of GNL distortions can be reduced by using a continuous moving table acquisition[95] or by breaking up the S-I FOV into multiple table stops and "stitching" the acquired images together to generate one continuous, large FOV acquisition[33]. Note that stitching will increase total scan time and may require specialized software on console or in a post-processing toolkit to enable image combination.

7.6 Metal Artifact Reduction Sequences (MARS)

The presence of metallic implants can cause signal loss, signal pileup and distortion due to differences in magnetic susceptibility between the metal and surrounding tissue, thereby complicating target and organ at risk identification and contouring. SE-based pulse sequences are preferable to GRE sequences since GRE is more vulnerable to signal loss and artifacts from metal. Increasing the receiver and excitation bandwidth also helps minimize susceptibility artifacts from metal but may not eliminate them[96]. Recently, many vendors have introduced advanced reconstruction methods that combines view-angle tilting (VAT)[97,98] and slice-encoding metal artifact correction (SEMAC)[99] that further allows in-plane and through-plane susceptibility artifact correction. VAT uses an extra gradient in the slice select direction during the signal read-out, and the slice is effectively viewed from an angle whereas SEMAC augments the VAT method with phase encoding in the slice direction.

7.7 Respiratory motion management

In Diagnostic Radiology, motion management is implemented to reduce image artifacts, particularly in the abdomen and thorax. In radiotherapy, motion management must additionally provide

those images at specific motion states congruent with those used for treatment delivery. Modern MRI scanners offer a number of approaches to manage respiratory motion, including breath holds, respiratory-triggered acquisitions, and motion insensitive pulse sequences.

7.7.1 Optimization of respiratory motion management

Breath hold imaging typically uses fast GRE sequences with partial Fourier acquisition, parallel imaging, and reduced phase resolution to limit scan times to 15-20 seconds (the shorter for end-expiratory breath holds). Breath hold sequences often reduce image artifacts during acquisition of multi-phase dynamic contrast T1-weighted images in the abdomen and thorax.

Respiratory-triggered acquisitions use a surrogate signal during acquisition. Surrogates can mimic those used in CT (e.g., pneumatic bellows) or can be unique to MRI (e.g., pencil beam[100] or phase-based internal navigators[94]). MR navigators are prepulses that image small FOV, high contrast interfaces (e.g., lung/liver, kidney/peri-renal fat, etc.) or phase sensitive interfaces in planes perpendicular to motion. The signal from the navigator is used to synchronize image acquisition at a specific trigger point to minimize motion artifacts (note that the navigator cannot run concurrently with image acquisition). The trigger level and trigger delay must be optimized to ensure the acquisition is performed at the desired respiratory phase. In addition, the acquisition length per trigger event must be optimized by adjusting the number of concatenations (Siemens), packages (Philips), or acquisitions (GE). This ensures that the entire prescribed volume is acquired at a specific respiratory phase at the expense of increased total acquisition time. Recently, self-navigated sequences have emerged that infer the position of the diaphragm in real-time using acquired data for retrospective respiratory gating while reducing pencil beam artifacts[78]. A dynamic motion phantom, driven by actual patient waveforms, is recommended to verify that triggered images are consistent with the required respiratory motion state. Respiratory-triggered acquisitions are often implemented to acquire T2 and DW images in the abdomen and thorax.

Conventional spin warp sequences utilize Cartesian sampling of k-space. While this is time efficient, reduces timing delay errors, and permits straightforward acceleration, Cartesian sampling exhibits increased sensitivity to motion. As an alternative, non-Cartesian k-space sampling can sample the center of k-space with each excitation, thereby increasing motion resilience[94,101]. Radial k-space sequences are one category of motion insensitive sequences now becoming commercially available for clinical applications.

7.7.2 Peristaltic motion management

Administration of anti-peristaltic agents can reduce blurring due to bowel motion in abdomen and pelvis disease sites. The onset of action and half-life of anti-peristaltic agents is dependent on route of

administration. Generally, two half doses of anti-peristaltic agents, administered intravenously at the beginning and mid-way through the MR-SIM exam is an effective means of minimizing peristalsis-induced motion[33]. Clinicians should consider the side effect profile when determining use for MR-SIM.

7.8 Reconstruction/post-processing considerations

7.8.1 Correction of GNL distortions

While the strategies in the previous section reduce the severity of GNL distortions, GNL distortions must still be corrected. MRI vendors provide integrated GNL distortion correction algorithms within the image reconstruction pipeline. Note that not all default distortion settings in clinical protocols arriving from the vendor are set with 3D GNL distortion corrections enabled, thus clinical physicists must ensure that 3D GNL distortion correction is enabled on all clinical MR-SIM protocols. It is important to note that residual geometric distortions exceeding several millimeters may persist for large FOV prescriptions following vendor-provided 3D GNL distortion correction which has been shown across several magnets and vendors (see section 9.1) [36,67]. The severity and position of these residual distortions should be characterized on each MR system as outlined in Section 6.2.2. Depending on their severity and proximity to target volumes, residual GNL distortions should influence margins.

7.8.2 Correction of image intensity non-uniformities (IINU)

Variations in the RF transmit field, RF receive coil sensitivity profiles (B_1^-), and the RF wavelength in the patient being imaged can result in IINU[17], or low frequency intensity variations that may affect intensity-based image registration, segmentation algorithms, and quantitative evaluation of treatment response[18,19]. MRI vendors provide integrated algorithms (pre-scan normalize, CLEAR, and PURE, for Siemens, Philips, and GE, respectively) in the image reconstruction pipeline to compensate for variations in the RF receive field arising from differences in the sensitivities of phased-array RF coils positioned around patients during imaging. It should be noted that residual IINU may exist following correction.

7.9 Additional Considerations

7.9.1 Optimization of diffusion-weighted imaging (DWI)

Clinical DWI is typically acquired using a single-shot, spin echo, echo-planar imaging (EPI) pulse sequence. Although this sequence is robust against motion, the low effective bandwidth along the phase-encode direction increases the sensitivity of the EPI sequence to off-resonant spins and can result in global and local geometric distortions along the phase-encode direction[40]. Optimization of DW sequences involves several factors: 1) controlling chemical shift, 2) reducing the total time duration of the EPI readout, 3) controlling eddy currents, and 4) maximizing SNR. Chemical shift can be controlled by prescribing fat

pre-saturation pulses or by using water excitation pulses. The total time duration of the EPI readout can be controlled by simultaneously: i) enabling parallel imaging acceleration (e.g., SENSE, GRAPPA), ii) enabling partial Fourier acquisition, iii) optimizing the readout bandwidth to minimize the effective echo spacing of the EPI readout (i.e., the time between gradient echoes)[94]. Additional optimization includes prescribing the minimum echo time (TE), performing careful high order shimming over a localized shim volume, and considering use of tailored phase-encode directions (for example, running the phase-encode direction left-right may be useful in reducing geometric distortions arising from gas bubbles in the rectum in prostate and cervix MR simulation exams).

To minimize susceptibility-induced distortions arising from EPI sequence, DWI may also be acquired using TSE/FSE based acquisition. TSE-based DWI acquisition refocuses the effect of static field inhomogeneities, increasing the signal at a given echo time and permitting longer sampling windows, higher voxel bandwidths, with less spatial distortion than EPI-based DWI. However, the inclusion of diffusion weighting gradients in a TSE sequence may lead to phase errors. The destructive interference between spin echoes and stimulated echoes may create unstable TSE trains and ultimately signal loss or signal voids in DW-TSE images. Various approaches such as phase recycling[102], echo parity[103], and modifying k-space view ordering[104] have been used to create more stable echo trains. Using a short refocusing pulse and modifying the k-space view ordering have also been implemented to further improve the SNR and blurring of TSE-based acquisition. Although the sequence suffers from slightly lower SNR and longer acquisition times compared to EPI-based DWI, its robust geometrical accuracy is facilitating preliminary investigation for radiotherapy treatment planning applications[104-106] .

7.8.2 Data utility

If images obtained from an MR simulator are to be interpreted by diagnostic radiologists and the state's CON does not prohibit use, diagnostic radiologists should be consulted during protocol development to ensure images are of sufficient quality to fulfill multiple roles of treatment planning and diagnosis. Similarly, if MR simulator images are to be used as baseline images for evaluation of treatment response, consideration should be given to minimize disagreement with diagnostic MRI protocols. At times, physicians may request MR images from outside institutions be loaded and registered for use in treatment planning. However, the reader is advised to use extreme caution in these scenarios because, generally, outside images may not have been acquired with an MR-SIM protocol optimized for RT and, thus, have no guarantee of geometric fidelity. Thus, it is recommended that these datasets not be loaded onto the planning systems and registered, but rather referenced on an auxiliary computer while contouring.

7.10 Example Failure Mode and Effects Analysis (FMEA) of a clinical workflow

As MR simulators are now being integrated into the clinic, it is important to identify potential high-risk areas that may require additional safeguards and QA procedures. To this end, a failure mode and effects analysis (FMEA) can be used to assess risk by identifying possible failure modes (FMs) that can occur throughout the entire workflow and prioritizing actions to reduce risk based on three major aspects: (1) the severity of the effects from FMs (S), (2) their frequency of occurrence (O), and (3) the detectability of their occurrence (D)[107,108]. Recent work conducted by Kim *et al.* performed FMEA on the implementation of MR-SIM for prostate cancer external beam prostate radiation therapy using the conventional CT+MR workflow[109]. A nine-member multi-disciplinary team (three medical physicists, two radiation oncologists, two radiation therapists, and two MR technologists) performed process mapping and identified FMs. The team also performed S, O, and D scoring per the ranking system defined in the AAPM Task Group 100[107] to derive risk priority numbers (RPNs) via the product of S, O, and D as a metric for evaluating relative patient risk. Notably, the image fusion and target delineation sub-processes added 19 total FMs (six greater than 100). The highest RPN values were calculated for poor image fusion quality and misinterpretation of multi-modality information leading to inaccurate delineation (RPN range: 120-192). A detailed fault tree analysis for one of the most significant FMs (inaccurate localization of the tumor volume) has been described[109]. Here, four failure pathways with 14 branches were identified, where each pathway consisted of one or more technical failures along with a failure in supervision, often caused by inadequate training of the person overseeing the MR-SIM process. For an abdominal cancer use case, additional failure modes may be introduced due to geometric uncertainties in respiratory motion management between MR-SIM and CT-SIM although the quality management protocol provided in Appendix A (MR-SIM Patient QA Checklist) includes safeguards for each of these issues. Another area that has been evaluated via FMEA in detail previously and not unique to MR simulators is regarding MR safety and contraindications to MRI[110]. Here, one of the highest failure modes was the MR screening form incorrectly filled out, with potential catastrophic consequences.

8. UNMET NEEDS AND FUTURE DIRECTIONS

8.1 3D Gradient nonlinearity distortion correction

For some vendors, 3D GNL correction can currently only be performed on images acquired with 3D pulse sequences (i.e., 3D GNL correction cannot be applied to multi-slice 2D acquisitions including respiratory gated or triggered images, DW images, etc.) and may only be available for a subset of 3D pulse sequences. While most vendors include 3D GNL correction during image reconstruction, 3D GNL correction may not be able to be applied retrospectively. The QMP should consult with the vendor to understand these limitations on their particular MR simulator platform.

8.2 Online B_0 field mapping

B_0 field maps may be used for routine QA as well as the assessment (and possible correction) of patient-specific geometric distortion. At present, online B_0 field mapping functionality is limited and may require purchasing advanced research capabilities. It should be noted that some of the B_0 field maps generated by the vendors use wrapped phase images, which can introduce errors if used in subsequent analyses. The QMP should consult with the vendor whether online B_0 field mapping functionality is available and, if so, whether the input phase images are unwrapped or will require phase unwrapping before use. Efforts to develop rapid methods to assess B_0 field maps from commonly acquired sequences such as generalized multi-point Dixon (mDIXON)[111] are currently under development[112].

8.3 Online geometric distortion correction

With a B_0 field map of the patient and knowledge of the scan parameters of each image, it is possible to apply algorithms to correct images for geometric distortions[62,113]. At present, no MRI vendor provides online geometric distortion correction of MR images. An alternative to online geometric distortion correction of MR images may be to spatially-restore distorted contour coordinates. These contour correction algorithms could be implemented into delineation or radiation treatment planning systems. An alternative to online geometric distortion correction and contour correction is to generate a voxel shift map (voxel displacement map) based on a B_0 map of the patient and knowledge of the imaging parameters from the DICOM headers[114]. Contours could be overlaid onto the voxel shift map, where they can be interrogated to determine whether a larger margin is warranted in regions of larger geometric distortions.

8.4 4D-MRI

Vendor offerings are currently limited for respiratory-correlated 4D-MRI, with most implementations performed under research agreements with specialized software[78,79]. Ideally, 4D-MRI would be obtained by dynamic, real-time imaging of 3D volumes. However, acquisition and reconstruction of real-time 3D volumes that meet the unique spatial, temporal, and contrast resolution constraints of radiotherapy is not yet possible. As an alternative, respiratory-correlated 4D-MRI via retrospective sorting[115-117] or prospective triggering[53, 95-97] has gained a large interest in the research setting as an alternative to 4D-CT for the characterization of respiratory motion throughout the thorax and abdomen.

8.5 Residual GNL corrections or isodistortion contour display

Residual GNL distortions may persist at large FOVs following the application of vendor provided 3D GNL correction. These may be further corrected by applying phantom-based 3D distortion maps obtained with reversed gradient sequences as described in Section 6.2.2. Alternatively, isodistortion

contours could be generated in DICOM format to be overlaid with patient images in the TPS to highlight the local magnitudes of residual distortion. No vendor-provided solutions to correct for residual GNL distortions currently exist.

8.6 Residual IINU corrections

Vendors provide algorithms that mitigate variations in the B1- field arising from differences in phased-array RF coil sensitivity profiles. However, additional corrections may be required to reduce residual IINUs in order to achieve optimal results with intensity-based image registration and segmentation algorithms. These algorithms could be integrated on the scanner console or within image registration, delineation, or treatment planning systems. At the time of this writing, only research solutions for residual IINU corrections exist[118].

8.7 DICOM header screeners

There is strong potential for DICOM headers to be interpreted by third-party image registration, delineation, or treatment planning systems to identify images acquired using a non-RT-specific imaging protocol before they are used clinically. Once identified, it may be possible to retrospectively correct datasets, reference them on an auxiliary system for delineation (in lieu of co-registering them), or inform the end-user of potential acquisition conditions that may reduce the accuracy of the dataset such as low readout bandwidth or vendor-supplied distortion correction (2D or 3D). Standardized reporting of such parameters remains an unmet need as GNL distortion information is currently defined in the private attributes of the DICOM header, thereby limiting interoperability and interpretation.

8.8 RT-Specific MRI sequences, RF coils, and affixed couches

Despite the strategies discussed to optimize DW images, local geometric distortions may still persist with EPI. Some scanner vendors offer alternative approaches to single-shot EPI for diffusion-weighted imaging[119,120]. Although these techniques may be successful in the brain or head or neck, effective solutions for body DWI are not clinically available across all MRI vendors at the time of this writing. Clinically released respiratory-correlated 4D-MRI sequences are also needed.

One factor contributing to IINU is the lack of optimized RT-specific RF coils designed to accommodate patients immobilized in treatment position while providing increased SNR and acceleration. This is particularly problematic for head and neck MR-SIM. Recently introduced adaptive image receive coil technology permits individual coil elements to be positioned directly on immobilized patients, permitting increased SNR, acceleration, and accommodation of RT setups[121]. However, at the time of this writing, this technology is only available under research agreements.

While the majority of MRI manufacturers offer dockable tables to improve patient throughput, the mechanical accuracy will be less than if the tabletop were affixed as in CT-SIM and on the delivery systems. Future development to improve the performance and stability of detachable tables is warranted.

8.9 MR-only Treatment Planning

MR-only based treatment planning, where synthetic CT data is generated from MRI and used for dose calculation, has been under research and clinical development in recent years[17]. Methods to generate synthetic CTs have largely included voxel[122] and atlas-based approaches[17,123,124] and more recently, deep learning[125-128]. At present, three clinically released MR-only packages are available: (1) Philips MR-CAT is FDA-approved for pelvis and integrated inline with the MRI reconstruction software via a dual echo 3D mDIXON fast field echo sequence and assigning bulk HU values for air, adipose, water, trabecular/spongy bone and compact/cortical bone[129], (2) Spectronic's MriPlanner is regulatory approved (CE-marked) and generates a synthetic CT using a statistical decomposition algorithm[130] via a single T2-weighted input, and (3) Siemens offers a brain synthetic CT solution including several input images such as ultra-short echo time to differentiate bone.

9. CONCLUSIONS

Overall, this task group report addresses the needs and considerations associated with an MR-SIM program including major equipment, MR safety, QA processes, staffing, and clinical implementation. The program set forth in this report was designed with consideration for improving the accuracy of patient information integrated into treatment planning while still considering efficiency and resources. The implementation of the recommendations will depend on the specific model implemented at individual institutions however the described principles should be employed whenever possible. While new MRI technologies continue to be introduced and their use expanded in Radiation Oncology, this document is expected to serve as a foundational framework for establishing and maintaining an MR-SIM program.

Disclosure Statement

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Figure Legends

Figure 1: Example setup for a pelvis or abdominal case with major equipment such as the flat table overlay and radiofrequency (RF) coils and coil bridge depicted.

Figure 2: Large field of view landmark phantom with embedded fish oil capsules and imaged on a 1.0T MR simulator with raw data reconstructed with no vendor provided gradient non-linearity corrections, two-dimensional (in-plane) corrections, and three-dimensional (in- and through-plane) distortion corrections applied. Note the restoration of the grid pattern in the sagittal plane is improved with 3D corrections although some residual uncertainty is still present necessitating a thorough characterization by a qualified medical physicist.

Figure 3. Conventional (a) and reversed (b) simulation workflows. Processes denoted in red denote additional steps required to ensure compatibility with MR simulator equipment and high quality MR imaging.

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Appendix A

MR-SIM Patient QA Checklist

Patient Name: _____ MRN: _____

		Therapist Checklist
Setup	Patient screened for MRI Safety	
	Patient changed into gown	
	Organ at risk (OAR) filling protocol administered (if applicable)	
	IV access obtained and contrast injector loaded (if applicable)	
	Prior images of patient reviewed on PACS system	
	Flat table overlay positioned on MRI couch	
	Immobilization devices fit within MRI bore and RF coil plugs have access to terminals	
	External lasers reset (zeroed) prior to setting up patient	
	Ear plugs or headphones placed on patient	

RF coils secured on bridges or with brackets and positioned close to patient surface	
Antiperistalic agent administered (if applicable)	
Emergency panic ball tested and positioned in patient hand	
Localizers External lasers turned off	
OAR filling matches planning CT (if applicable). If not, wait or intervene.	
Acquisition Center of prescription volume set to move to isocenter	
High order shim volume optimized and copied to each series	
Intensity uniformity correction enabled (Pre-Scan Normalize/CLEAR/PURE)	
Navigator position optimized at dome of liver (if applicable)	
Breath holds acquired at respiratory phase matching RT delivery (if applicable)	
Receiver bandwidths optimized per disease site (or 440/880 Hz/pixel at 1.5 T/3 T)	
Prescribed image volume/plane compatible with delineation software	
Metal artifact reduction sequences used for metallic implants (e.g., hip prostheses)	
3D GNL distortion correction enabled (3D Distortion/3D Correction/3D GradWarp)	
Images screened for artifacts. If necessary, resolve artifact source and re-acquire.	
Post-Scanning Setup reference point defined	
Confirm 3D GNL distortion correction performed on all images	
Images exported to delineation system	
Initials/Date	

Appendix B: Monthly Quality Assurance Template

1. Mechanical check

    a. External Laser

    Qualitative evaluation

	Yes	No	N/A
Do axial lasers match with each other within ±2mm?	☐	☐	☐
Do sagittal lasers match with each other within ±2mm?	☐	☐	☐
Do coronal lasers match with each other within ±2mm?	☐	☐	☐

Quantitative evaluation – Laser alignment with MRI isocenter

	Alignment accuracy (mm)	Tolerance
Axial lasers		±2.0mm
Sagittal lasers		
Coronal lasers		

Quantitative evaluation – Laser movement accuracy (if applicable)

	Set distance (mm)	-100	-50	-10	0	10	50	100
Axial	Measured distance (mm)							
	Deviation (mm)							
Sagittal	Measured distance (mm)							
	Deviation (mm)							
Coronal	Measured distance (mm)							
	Deviation (mm)							
	Tolerance	±1.0mm						

b. Table

Qualitative evaluation

	Yes	No
Does table move smoothly across clinical range?	☐	☐
With no accessories attached, does table move free of collision?	☐	☐

Quantitative evaluation – Table movement accuracy

Table in	Set distance (mm)	300	150	0	-150	-300
	Measured distance (mm)					
	Deviation (mm)					
Table out	Set distance (mm)	-300	-150	0	150	300

	Measured distance (mm)					
	Deviation (mm)					
Tolerance		±1.0mm				

Note: If the table is capable of vertical movement, its accuracy also needs to be tested. The set distances in the above tables are used as an example. It is recommended that individual cancer centers setup the set distances based on their machine capability.

2. Patient marking

	Yes	No	N/A
Axial laser marking accuracy within ±2mm?	☐	☐	☐
Sagittal laser marking accuracy within ±2mm?	☐	☐	☐
Coronal laser marking accuracy within ±2mm?	☐	☐	☐

3. Visual checklist (adapted from ACR MRI weekly visual checklist)

	Yes	No	N/A
Table position and other display	☐	☐	☐
Alignment lights	☐	☐	☐
Horizontal motion smoothness and stability	☐	☐	☐
Vertical motion smoothness and stability	☐	☐	☐
RF door contacts	☐	☐	☐
RF window-screen integrity	☐	☐	☐
Operator console switch/lights/meters	☐	☐	☐
Patient monitor (if present)	☐	☐	☐
Patient intercom	☐	☐	☐
Room temperature/room humidity	☐	☐	☐
Emergency cart	☐	☐	☐
Safety warning signage	☐	☐	☐
Door indicator switch (if installed)	☐	☐	☐
Cryogen level indicator	☐	☐	☐
Laser camera (if present)	☐	☐	☐
Light boxes (if present)	☐	☐	☐

4. Center frequency and transmitter gain

	Results	Tolerance
Center frequency		Manufacturer Specified
Transmitter gain		Baseline +/- 5%

5. Geometric accuracy (ACR sagittal localizer and T1-weighted axial images)

	Results	Tolerance
H/F sagittal localizer length		148±2mm
Axial slice #5 diameter (A/P)		190±2mm
Axial slice #5 diameter (R/L)		190±2mm

6. High-contrast spatial resolution (ACR T1-weighted axial images)

	Results	Tolerance
Highest resolved array (UL)		≤1.0mm
Highest resolved array (LR)		≤1.0mm

7. Low-contrast detectability (ACR T1-weighted axial images)

	Results	Tolerance
Slice # used for the test		No change from baseline
# of spokes detected in that slice		No change from baseline

8. Artifact evaluation (ACR sagittal localizer and T1-weighted axial images)

	Yes	No
Images free of artifacts?	☐	☐

9. Bore inspection for foreign metal

	Yes	No
Is scanner bore free of foreign metal?	☐	☐

Note: ACR sagittal localizer and T1-weighted axial images are acquired using the ACR large phantom.

Appendix C: MR Simulator sequence protocols for common disease sites

Table C.1: Example MR Simulator sequence protocols for several common disease sites. Readout bandwidth settings assume a permissible shift of 1 mm along the readout direction[1]. Image contrast parameters (TE, TR, TI, flip angle), spatial resolution parameters (slice thickness, oversampling factor), and SNR/acceleration parameters (averages, partial Fourier factor, parallel imaging reduction factor) should be optimized based on discussions among the MR SIM team.

Disease Site	Image Contrast	Pulse Sequence[2]	Field of View (mm)	Matrix Size	Readout Bandwidth (Hz/pixel)	Motion Management
Brain	T2 FLAIR	3D Spin Echo	240x240	256x256	340 (1.5 T) 654 (3.0 T)	N/A
	T1+Contrast	3D Gradient Echo				
Head Neck	Fat-Sat T2	3D Spin Echo	256x256	256x256	362 (1.5 T) 697 (3.0 T)	Coach to refrain from swallowing
	Fat-Sat T1+Contrast	3D Spin Echo				
Abdomen	Fat-Sat T2	3D Spin Echo	384x384	384x384	310 (1.5 T) 598 (3.0 T)	Respiratory triggering[3]
	Fat-Sat T1+Contrast	3D Gradient Echo				Breath hold[4]
Pelvis	T2	3D Spin Echo	384x384	384x384	310 (1.5 T) 598 (3.0 T)	Anti-peristaltic agent
	Fat-Sat T2	3D Spin Echo				
	Fat-Sat T1+Contrast	3D Spin Echo				
Image Uniformity Correction			Pre-Scan Normalize (Siemens), CLEAR (Philips), PURE (GE)			
Gradient Nonlinearity Correction			Distortion Correction Mode 3D (Siemens), 3D Compensation (Philips), 3D GradWarp (GE)			
Respiratory Triggering Readout Duration Parameters			Concatenations (Siemens), Packages (Philips), Acquisitions (GE)			

[1]Readout bandwidths may be relaxed according to Equation 2 if a larger permissible shift is deemed acceptable by the MR SIM team.

[2]3D pulse sequences are recommended due to availability of 3D GNL correction algorithms across imaging vendors. If imaging vendors support 3D GNL correction for multi-slice 2D sequences, then these sequences can be substituted at the discretion of the MR SIM team.

[3]Optimize readout duration of respiratory triggered sequences to ensure images are only acquired during intended respiratory phase.

[4]Match breath hold position (e.g., inspiration or expiration) to position used for RT delivery

Table 1: Major MR simulator equipment and considerations.

Major Equipment	Function	Recommendations/Considerations
Flat table overlays and inserts	• Mimic CT-SIM and treatment position • Index MR-safe/conditional devices	• Minimize distance between patient and RF coils/thin construction to avoid SNR and uniformity degradation[28,29 30, 31] • Indexing capability • Appropriate width to accommodate coils and immobilization devices (i.e. head and neck support system may require a specific overlay width) • Low magnetic susceptibility materials • Stable translation over scanning range
Detachable couch/patient handling system	• Handling and transfer of patients in treatment position	• Facilitates patient transfer between imaging and ancillary locations • Permits immobilization device construction outside magnet area for efficiency considerations, particularly in shared resource settings • Enables immediate removal of patients from Zone IV (MR scanner room) in the instance of a medical emergency • Must be free to move during power failure
External laser positioning and marking system (ELPS)	• Expedite patient setup • Facilitate patient reference point marking	• Integrated rigid bore-mounted lasers not sufficient for patient alignment and marking due to: limited longitudinal coverage, inability to assess rotation, susceptibility to magnet vibrations, and limited ability to make fine adjustments to position/rotation of bore-mounted lasers without cover removal. • ELPS have fixed longitudinal distance from magnet isocenter • Laser bridge should not restrict/block access to scanner

		• It should be verified that lasers can be located within the fringe field of the MR scanner. • Must be installed close enough to facilitate marking of superiorly positioned patients (i.e., brain) when couch moved out of the magnet to home position.
RF coils	• Detection of MRI signal	• Flexible surface coil arrays permit highest conformality around immobilized patients and their immobilization devices, thus maximizing SNR • Cable length sufficient for variable setup conditions • Posterior coil array may be built into the table
Coil bridges	• Prevent RF coil weight from deforming external anatomy (~1.7 cm displacement noted[41])	• Adjustable positioning preferred to minimize separation between patient and RF coils (signal degrades rapidly with increased separation)

Table 2: Factors affecting siting and relevant sources for guidelines/limits

Test / System	Protocol / Parameter / Tolerance	Potential Impact	Reference / Guideline	Personnel (R = Required, O = Optional)
Fringe fields	Identify 500 Gauss, 100 Gauss and 5 Gauss lines (5 Gauss posted) Areas with B_0 > 5 Gauss require controlled access (SI unit conversion: 1 Gauss = 0.1 mT)	Safety considerations	FDA premarket certification guidelines[45] Fringe field map and siting requirements for MR simulator provided by vendor	R: MRI trained diagnostic physicist, vendor personnel O: Therapeutic medical physicist
	Determine fringe field limits for adjacent sensitive equipment such as imaging equipment, other MRIs, and linear accelerators.	May influence performance of adjacent equipment	Adjacent equipment limits provided by individual manufacturer	
RF shielding	Appropriate attenuation of external RF sources within RF enclosure. Electrical isolation from building ground	RF interference impacting image quality	Vendor specified attenuation level (dB), RF frequency, and DC electrical isolation.	R: MRI trained diagnostic physicist, vendor personnel O: Therapeutic medical physicist
Equipment room siting and power considerations	Verify vendor specifications can be met before installation	May require ad hoc adjustments to RF shielding or wiring	Per vendor guidelines	R: MRI trained diagnostic physicist, therapeutic
	-Ample filtered AC power outlets in magnet room			

	-Adequate number of AC power outlets in control room			medical physicist, vendor personnel

Table 3: Subsystems of the MR scanner, associated safety risks and regulatory limits.

MR Scanner System	Associated safety risk	Considerations/Limits	Regulatory agency/Reference
Main magnetic field (B_0)	Projectile effect of ferrous metals	Exclusion of all ferrous objects from Zone IV	FDA (non-significant risk criteria)[50]
	Torque of implanted devices	Device-specific evaluation of utility and implantation site as well as manufacturer recommendations for MR imaging	
	Disruption of implanted device function / alteration of device settings.	Compliance with manufacturer guidelines for safe MR scanning of device	
Gradient system	Peripheral nerve stimulation		US FDA, IEC[51]
	Acoustic noise	Amplitude-weighted root mean square (rms) sound pressure level >99 dB, personnel and patients should wear hearing protection (ear plugs and ear muffs when possible) when in MR scan room during imaging	US FDA, IEC[42,51]
Radiofrequency (RF) system (B_1)	Heating	Guidelines for maximum RF power deposited as measured by specific absorption rate (SAR, units	IEC, US FDA[52]

		of W/kg)[52]. Typical IEC operating modes (normal, first level controlled, and second level controlled).	
Cooling System	Cryogen Cooling Agents (Liquid Helium)	-Cryogen venting via a discharge pipe in the event of a quench (major loss of coolant). Release of helium may displace oxygen in room leading to asphyxiation hazard. All persons must be evacuated and access shall be restricted until service personnel arrive. -Oxygen monitoring control units sited in MRI electronics room with visual alarms visible in control room	AAPM Report 20[44]

Table 4: Operational models and their characteristics in an MR simulator environment.

Operational Model	Definition	Potential Roles	Advantages	Disadvantages
Traditional	Personnel work in professional training capacities	• ARRT-certified MR technologist operates MR scanner • ARRT-certified radiation therapist performs patient immobilization and setup • MRI physicist performs acceptance, commissioning, and ongoing QA	• Level 2 personnel requirements met using dedicated MRI staff • Personnel comfortable in standard roles • Formal didactic training programs completed • MRI expertise established	• If MR simulator is a dedicated resource, may not require full FTEs • Training required for diagnostic staff to understand simulation objectives
		•	•	•

Table 5: Key personnel on an MR-SIM team, their full-time effort (FTE) during initial (i.e., first 1-3 months) and ongoing periods of the MR-SIM program, and possible roles assuming the Traditional Operational Model is followed. Data presented are based on consensus from Task Group member recommendations.

Team Member	**Initial FTE (cal. months)**	**Ongoing FTE (cal. months)**	**Major roles**
Therapy Physicist	1-2	3	**Initial FTE:** • Equipment selection • RT specific acceptance testing and commissioning/baselines • RT scan protocol optimization (initial) **Ongoing FTE:** • Image registration QA • Education • Process management and documentation • RT scan protocol optimization (new indications) • Manage and conduct QA program • Data management
Diagnostic/ MRI Physicist	1-2	1	**Initial FTE:** • Equipment selection • Magnet siting/room design • Acceptance testing and commissioning/baselines and training therapy physicist • RT scan protocol optimization (initial) • Acceptance testing, ACR accreditation if applicable • Education **Ongoing FTE:** • Education • RT scan protocol optimization (new indications) • Special consult (special patient conditions/implants/contraindications)
Radiation Therapist	N/A	12	• Prepare room/immobilization device support • Perform patient setup in treatment position • Patient workup for contrast contraindications

			• Documentation in record and verify system (patient, QA), MR-SIM Patient QA Checklist (Appendix A) • Initial evaluation of contraindications found on initial screening
MR Technologist	N/A	12	• Perform daily, weekly QA and phantom scanning • IV placement/contrast administration • Final MR safety screening • Investigating potential contraindications • Patient scanning • Feedback on image quality • Data handling/transfer • Post-processing steps
Radiologist	0.5	0.5	• Feedback on RT scan protocol optimization (initial, new indications, sequence selection) • Interpretation of MR-SIM images if requested • Education • Clearing implants/contraindications
Radiation Oncologist	0.5	0.5	• Feedback on RT scan protocol optimization (initial, new indications, sequence selection, scan length/FOV) • MR-SIM request note/physician directive • Placement of ancillary materials/devices • Tumor localization and delineation
Dosimetrist	N/A	0.5	• Feedback on image quality • Image registration QA • Delineation • Data import into TPS, management
Nursing	N/A	0.1	• Initial MR safety screening • IV/catheter placement and possible contrast administration • Administration of sedatives if required

Table 6. Commissioning, annual, and after major software or hardware component change quality assurance to be conducted by a Qualified Medical Physicist. More detailed descriptions of the preferred testing methodologies are described in the text. Recommended frequency defined in the table: C = commissioning, A = annual, E = equipment change. New tasks in an MR-SIM environment are highlighted with an asterisk. Tolerances may also be obtained by data sheets provided by scanner vendor.

Performance Parameter	Suggested Equipment	Suggested Method(s)	Tolerance/Reference	Recommended Frequency	Potential Clinical Impact
Magnetic Field Drift Test	Homogeneous spherical or cylindrical phantom	• Image with spin-echo sequence • Record central frequency value	<1 ppm/day during acceptance testing[56] < 0.25 ppm / day for first 1-2 months operation[56]	C, E	-Reduced SNR -Detrimental to functional/diffusion MRI -Unavailability of system if major repair required
Transmitter and Gain Calibration	Homogeneous spherical or cylindrical phantom with uniform insert	• Perform auto-prescan for clinical sequences, compare to manual prescan • Record central frequency, transmit, and receive gains • Determine transmit gain following TG 1, Report 100[55]	• No visible artifacts • Manually determined transmit gain values with ± 5% of those determined automatically • Manual versus automatic center frequency ± 10 Hz[56]	C, E, A	-Image artifacts (ghosting) -Low SNR -Poor uniformity -Unavailability of system if major repair required
Transmitter Gain Stability	Vendor specified	• Vendor specified	Vendor specified minimum amplitude, frequency, and phase stability levels unless otherwise agreed upon[56]	C, E	-Image artifacts (ghosting) -Low SNR -Poor uniformity -Necessary for high performance/fast sequences
Magnetic Field Homogeneity (B_0)	Spherical homogeneous phantom 24-35 cm diameter as	Preferred: Phase-difference Map[57]	<0.5 ppm volume root mean square (VRMS) across a 35 cm diameter spherical volume[55] or as	C, E, A	-Non-uniformity of fat suppression -Image nonuniformity

	recommended by MRI manufacturer, assessed in all three cardinal planes	• Let phantom to equilibrate for 30 minutes prior to measurement Acceptable: Phase Map, Spectral Peak, Bandwidth difference[57]	specified by MRI manufacturer across a specified DSV[57]		-Contributes to geometric distortions
*Characterization of Residual Gradient Nonlinearity (GNL)	In-house or commercial large (>80% of useable FOV) phantom with embedded landmarks	1. Preferred: Reverse gradient technique[58] • Acquire images with vendor 3D distortion corrections enabled with readout bandwidth set to twice the fat-water shift • Average landmark locations • Compare landmark centroids to reference data 2. Acceptable: Spherical Harmonics Analysis.[59] • Acquire data with boundary landmark phantom	≤ 1 mm (within 10 cm radial distance of isocenter) ≤ 2 mm (<25 cm radial distance away from magnet isocenter)[58]	C, E	-Reduced geometric fidelity away from magnet isocenter -Inaccurate localization of organs at increased distances from isocenter

		• Estimate distortions via spherical harmonics			
Radiofrequency Coil Evaluation	Uniform phantom of similar size to body site of interest	Method acceptable by ACR[57]	Coil dependent, action limit of ± one standard deviation determined by QMP via several baseline measurements Minimum criteria may need to be met if magnet is ACR accredited	C, E, A	-Reduced SNR -Non-uniform image
*Determine or verify external laser offset from MR isocenter	Phantom with scribes and internal landmarks for imaging	After verifying laser coincidence, level and align phantom to external lasers, translate couch known distance, acquire MRI, determine offset, iterate until tolerance is met.	≤ 1 mm	C, E, A	-Offset between patient and external lasers -Increased uncertainty in patient marking
*Table Alignment with B_0	Grid phantom	• Image with high-resolution spin echo sequence (0.5 mm in-plane resolution) at three couch positions along bore • Determine angle of grid phantom and vertical offset at each couch position	0 ± 0.3 degree between table and B_0 (cylindrical bore magnets) 90 ± 0.3 degree between table and B_0 (open bore magnets) <0.5 mm discrepancy in vertical offset	C, E	-Potential rotations or skewing of image volumes -Inaccurate laser marking

Informatics/ connectivity/ Data transfer	Phantom with landmarks noted for orientation	Ensure scanner is interfaced to required DICOM locations (e.g., Treatment Planning System, PACS and archive)	Site specific Per TG-248 guidelines**Error! Hyperlink reference not valid.**	C, E	-Workflow interruptions -Incorrect orientation
*Motion Verification	MR-compatible 4D motion platform	Play motion phantom with known waveform frequency and amplitude. Acquire dynamic images. Acquire respiratory triggered images using navigator or pneumatic bellows.	Amplitude based on prescribed motion waveform: • Preferred: 1 mm • Acceptable: 2 mm[60] Triggered acquisition window duration: • 30% of prescribed motion cycle Triggering delay: • Acquisition window centered over desired region of prescribed motion cycle	C, E	-Over/underestimate of target/OAR displacement -Inaccurate ITV estimation -Incorrect motion state of triggered images
*End-to-end Testing	Phantom with size, immobilization, and RF coil configuration per clinical use case (i.e., ACR MR quality	• Complete for clinically applicable workflows (CT/MR-SIM, reverse workflow, MR-only) for	Data integrity verified via TG53[61] Verify image orientation Concordance of external laser system/landmarks:	C, E	-Workflow interruptions -Localization inaccuracy -TPS incompatibility -Incorrect patient orientation

	control phantom for head)	common disease sites (head, abdomen/pelvis, extremities) • Image with optimized imaging protocols • Transfer/import data to TPS and verify: -Concordance of coordinate systems/orientation -Geometric integrity -Concordance of external laser system coordinates and spatial landmarks -Rigid co-registration accuracy between MR/CT	Preferred: 1 mm Acceptable: 2 mm Co-registration: Maximum cardinal direction error less than 0.5*voxel dimension size[62]		
Emergency Testing/Patient Monitoring	N/A	• Verify quench circuit and cryogen exhaust system with vendor	Functionality	C	-Patient/personnel safety concerns
		• Emergency stop/shutdown • Ensure that all patient monitoring systems (audio/visual) are functional and operate per manufacturer's specifications • Verify initial operation of all monitoring and emergency	Functionality	C, E	-Patient safety concerns

		systems – squeeze ball, respiratory bellows, ECG/pulse plethysmograph gating • Verify quench circuit viability with MRI vendor			
Eddy current compensation	N/A	• Two measurement methods (Integrator circuit or effect on signal from sample) described[63] to be conducted with installation engineers and agree with the vendor-provided report[55]	Verify vendor specification is met	C, E	-Image artifacts -Reduced SNR
Protocol/ Sequence Transfer	N/A	• Verification of data transfer	Verification	C, E	-Workflow interruptions -Modified parameters -Missing functionality
Optional: High performance imaging	Specialty phantoms (e.g., QIBA DWI or ice phantom)	Prescribe DWI sequence according to QIBA DWI profile. Acquire DW images in phantom.	Per QIBA Profile: Diffusion-Weighted Magnetic Resonance Imaging (DWI)[64]	C, E, A	-Image artifacts -DWI SNR -ADC bias -Inaccurate target shape/position -Low SNR leading to inaccurate ADC values

Table 7: Recommended monthly quality assurance tests, phantoms, tolerances and references for an MRI simulator program.

Test	**Suggested Equipment**	**Protocol / Parameter / Tolerance**
System		
Room temperature and humidity	Visual inspection of digital readout	Functional
Cold head operation	Audible pump sound	Functional
Cryogen level indicator	Digital readout from MRI console	Manufacturer specified (no change from baseline)
Mechanical		
Table movement smoothness and accuracy	Ruler	±1.0 mm from set distances
Laser alignment with imaging isocenter	Ruler and phantoms with internal landmarks	±2.0 mm from expected distance offsets
Laser movement smoothness and accuracy	Ruler	±2.0 mm from set distances
Patient marking		
Laser marking accuracy	Patient marking software	±2.0 mm
Image quality*		
Central frequency	Digital readout from MRI console after imaging reference phantom (i.e., ACR large MRI phantom or homogeneous phantom)	Manufacturer specified
Transmitter gain		± 5% from baseline
Flexible RF coil testing	Homogeneous phantom	Individual elements, exceeds minimum vendor-provided threshold

Geometric accuracy	Manufacturer supplied, in-house, or commercially available phantom > 30 cm in diameter/width	Verify ≤ 2 mm across 25 cm FOV
High contrast spatial resolution	ACR large MRI phantom with procedures/tolerances defined in Ref. 62	≤1.0 mm
Low contrast detectability		Total number of discernible spokes (for 4 slices) for fields <3 T should range from 21 (0.3 T) to 36 (1.5 T), and 40 for 3 T.
Artifact evaluation		No obvious image artifacts
Percent image uniformity		Head coil: ≥ 87.5% for < 3 T ≥ 82.0% for 3 T
Percent signal ghosting		Ghosting Ratio ≤ 2.5%

*May skip measurement if weekly ACR MRI QA results performed by Diagnostic Radiology Department staff are made available for the QMP to review. Baseline values shall be established following the ACR 2015 QC Manual (collect data for 10 days and determine baseline value). Action limits will be magnet and system-specific as determined by the QMP and manufacturer recommendations.

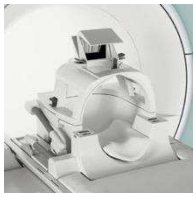
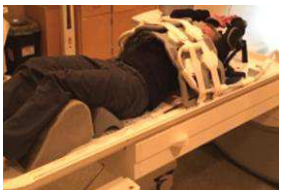
Table 8: Recommended daily quality assurance for an MR simulator program.

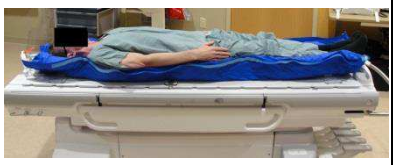
Test / System	Suggested Equipment	Protocol / Parameter / Tolerance
Safety		
Functionality of patient communication and monitoring	N/A	-Patient monitoring systems (audio/visual) functional -Emergency squeeze ball functional
Emergency cart or emergency couch release	Visual inspection	Exist
Safety signage	Visual inspection	Exist
Check bore for presence of foreign metal objects	Visual inspection	-None present. -If detected, large volume phantom can be scanned with a GRE-based sequence with a low bandwidth to localize the metal to be removed by vendor personnel.
Mechanical		
External laser agreement with imaging plane	Phantom with scribes and internal landmarks for imaging	-Level phantom -Align to external laser -Translate known offset to magnet isocenter -Image phantom -Verify scribes are within ± 2 mm of central slice location
Image Quality		
Transmit gain Central frequency*	Digital readout from MRI console	<5% change from baseline Manufacturer specified
Basic coil SNR check	Manufacturer supplied or ACR large MRI phantom	-Combined elements, exceeds minimum vendor-provided threshold

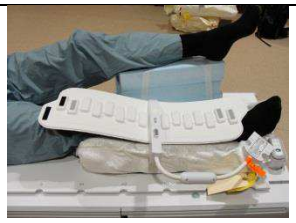
Basic spatial fidelity check	Manufacturer supplied or commercially available phantom	-Verify ≤ 2 mm across 25 cm FOV

*May skip measurement if weekly ACR MRI QA results performed by Diagnostic Radiology Department staff are made available for the QMP to review. Baseline values shall be established following the ACR 2015 QC Manual (collect data for 10 days and determine baseline value). Action limits will be magnet and system-specific as determined by the QMP and manufacturer recommendations.

Table 9: Disease site-specific MR simulation setups and considerations.

Disease Site	RF Coil Options	Example MR Sim Setup	Considerations
Brain	Flexible extremity coils	 	• Accommodates immobilization devices • Compatible with radiosurgery headframes • Compatible with MR-only workflow • Must be compatible with hearing protection • May result in reduced image quality compared to diagnostic coils
	Rigid, diagnostic head coils*		• Incompatible with immobilization devices • Additional channels improve image quality and reduce scan time. • Clinical decision with physician input based on image quality and registration uncertainty (~2 mm in brain[22,23])
Head and Neck	Combined flexible extremity, anterior array, and spine coils	 	• Combined coils provide coverage of entire head and neck region with good image intensity uniformity. • Posterior spine coil may be built into the table and thus compatible with immobilization • For sites with limited extent (i.e., larynx), a single anterior coil or two extremity coils may be sufficient for superior-inferior coverage. • Use of combined coils may require additional software to enable multi-coil image reconstruction.
Breast	Anterior array coils (Supine)		• RF coil bridges required to prevent RF coils from deforming breasts • May result in breasts being positioned in regions of high residual GNL distortions, requiring careful evaluation. • Patient incline limited by bore size and elbow position

			• Patient incline may increase risk of thermal burns arising from contact of extremities with bore. Use of insulating pads placed on extremities can reduce thermal burn risk.
	Diagnostic breast biopsy coils (Prone)		• Requires modification of diagnostic coil • Unilateral breast bridge required to block healthy breast • Reduced residual GNL distortions compared to supine breast setup • Clinical decision with physician input based on motion and disease location
Chest and Abdomen	Anterior and spine array coils		• Headphones support may be molded into alpha cradle/vac loc during formation • Abdominal compression devices can be integrated into setup • Anti-peristaltic agents may be used to suppress bowel motion. • Patient incline may increase risk of thermal burns arising from contact of extremities with bore. Use of insulating pads placed on extremities can reduce thermal burn risk. •
Pelvis	Anterior and spine array coils		• Anterior array positioned on bridges • Anti-peristaltic agents may be used to suppress bowel motion • Accommodates leg immobilization
Spine	Spine array coils		• Head and neck setup may be preferred for cervical spine • Long superior/inferior scan prescriptions may require step-and-shoot table movements to minimize residual GNL distortions • Accommodates immobilization device • Posterior spine coil may be built into the table and thus compatible with immobilization

Extremity	Anterior and spine array coils		• Attempt to position target volumes as close to isocenter as possible • RF coil bridges may be required to prevent RF coils from deforming surface anatomy • Long superior/inferior scan prescriptions may require step-and-shoot table movements to minimize residual GNL distortions • Patient position may increase risk of thermal burns arising from contact of extremities with bore. Use of insulating pads placed on extremities can reduce thermal burn risk.

*May not be done in treatment position due to tradeoffs with image quality