Published in final edited form as:

Med Phys. 2020 February ; 47(2): 604–613. doi:10.1002/mp.13951.

MRIGRT head and neck anthropomorphic QA phantom: Design, development, reproducibility, and feasibility study

A. Steinmann^{a)}, P. Alvarez, H. Lee, L. Court

Department of Radiation Physics, The University of Texas M. D. Anderson Cancer Center, Houston, TX 77030, USA

R. Stafford

Department of Imaging Physics, The University of Texas M. D. Anderson Cancer Center, Houston, TX 77030, USA

G. Sawakuchi, Z. Wen

Department of Radiation Physics, The University of Texas M. D. Anderson Cancer Center, Houston, TX 77030, USA

C. D. Fuller,

Department of Radiation Oncology, The University of Texas M. D. Anderson Cancer Center, Houston, TX 77030, USA

D. Followill

Department of Radiation Physics, The University of Texas M. D. Anderson Cancer Center, Houston, TX 77030, USA

Abstract

Purpose: The purpose of this paper was to design, manufacture, and evaluate a tissue equivalent, dual magnetic resonance/computed tomography (MR/CT) visible anthropomorphic head and neck (H&N) phantom. This phantom was specially designed as an end-to-end quality assurance (QA) tool for MR imaging guided radiotherapy (MRIGRT) systems participating in NCI-sponsored clinical trials.

Method: The MRIGRT H&N phantom was constructed using a water-fillable acrylic shell and a custom insert that mimics an organ at risk (OAR) and target structures. The insert consists of a primary and secondary planning target volume (PTV) manufactured of a synthetic Clear Ballistic gel, an acrylic OAR and surrounding tissue fabricated using melted Superflab. Radiochromic EBT3 film and thermoluminescent detectors (TLDs) were used to measure the dose distribution and absolute dose, respectively. The phantom was evaluated by conducting an end-to-end test that included: imaging on a GE Lightspeed CT simulator, planning on Monaco treatment planning software (TPS), verifying treatment setup with MR, and irradiating on Elekta's 1.5 T Unity MR linac system. The phantom was irradiated three times using the same plan to determine reproducibility. Three institutions, equipped with either ViewRay MRIdian ⁶⁰Co or ViewRay

^{a)} Author to whom correspondence should be addressed. aksteinm@umich.edu; Telephone: 713-745-8989.

CONFLICT OF INTEREST

There is no conflict of interest declared in this article.

MRIdian Linac, were used to conduct a feasibility study by performing independent end-to-end studies. Thermoluminescent detectors were evaluated in both reproducibility and feasibility studies by comparing ratios of measured TLD to reported TPS calculated values. Radiochromic film was used to compare measured planar dose distributions to expected TPS distributions. Film was evaluated by using an in-house gamma analysis software to measure the discrepancies between film and TPS.

Results: The MRIGRT H&N phantom on the Unity system resulted in reproducible TLD doses ($SD < 1.5\%$). The measured TLD to calculated dose ratios for the Unity system ranged from 0.94 to 0.98. The Viewray dose result comparisons had a larger range (0.95–1.03) but these depended on the TPS dose calculations from each site. Using a 7%/4 mm gamma analysis, Viewray institutions had average axial and sagittal passing rates of 97.3% and 96.2% and the Unity system had average passing rates of 97.8% and 89.7%, respectively. All of the results were within the Imaging and Radiation Oncology Core in Houston (IROC-Houston) standard credentialing criteria of 7% on TLDs, and >85% of pixels passing gamma analysis using 7%/4 mm on films.

Conclusions: An MRIGRT H&N phantom that is tissue equivalent and visible on both CT and MR was developed. The results from initial reproducibility and feasibility testing of the MRIGRT H&N phantom using the tested MRIGRT systems suggests the phantom's potential utility as a credentialing tool for NCI-clinical trials.

Keywords

dual modality QA phantom; end-to-end QA test; MRIGRT; MR Linacs; Unity; ViewRay

1. INTRODUCTION

New radiotherapy devices, referred to as magnetic resonance imaging guided radiotherapy (MRIGRT) systems, integrate an MR imager with either a linear accelerator or radioactive ^{60}Co sources. In the United States, there are presently three different MRIGRT prototypes which include: the Unity (Elekta, Crawley, UK), the MRIdian ^{60}Co (ViewRay, Oakwood Village, OH), and the MRIdian Linac (ViewRay, Oakwood Village, OH).^{1–6} In short, the Unity system is equipped with a 7-MV beam mounted to a slip-ring gantry located above a cylindrical 1.5 T wide-bore MR system. The MRIdian and MRIdian Linac systems are equipped with three ^{60}Co sources and a single 6-MV linear accelerator, respectively, that are centrally located within a split bore 0.35 T magnet.

The safety and usefulness of MRIGRT systems are still being investigated. The National Institutes of Health (NIH) has sponsored several short-term, preliminary clinical trials that investigate the safety issues in acquiring daily MR images ([NCT02973828](#)) and delivering radiation using MRIGRT systems ([NCT03284619](#)). Additionally, NIH-sponsored clinical trials ([NCT03048760](#) and [NCT01999062](#)) have begun to investigate how new MRIGRT workflows (i.e., online adapted radiotherapy) and advanced treatment techniques (i.e., auto-contouring, MR gating) would affect the clinic. NIH has also sponsored several short-term pilot studies ([NCT02264886](#), [NCT02683200](#), [NCT02701712](#), and [NCT02264886](#)) to investigate the effectiveness of using an MRIGRT system for various anatomical locations. While these pilot studies can, to some extent, determine regions that would likely benefit

from MRIGRT, more extensive multi-institutional clinical trials will be needed in the future to thoroughly evaluate clinical outcomes (i.e., local control, survival rates) for a given disease site. A proposed clinical trial could examine the correlation between local control rates and MR image guidance on an MRIGRT system.⁷ H&N region tumors would be ideal for this proposed clinical trial since computed tomography (CT) images lack soft tissue delineation.⁸

In order for radiotherapy centers to participate in large multi-institutional studies, the National Cancer Institute (NCI) requires each participating institution to be a part of IROC-Houston's QA program.⁹ Their QA program ensures all institutions participating in National Clinical Trial Networks (NCTN) can accurately and consistently deliver radiation doses to trial patients such as from intensity-modulated radiotherapy (IMRT) treatments. IROC-Houston has developed various on-site and off-site auditing tools to assure quality is maintained while participating institutions collect clinical data. Among such QA tools, IROC-Houston ships off-site anthropomorphic phantoms to credential NCTN trial participants using advanced technology treatment modalities.⁹ During the credentialing process, the phantom will undergo the same treatment workflow as a patient would and an end-to-end QA examination is performed to assess the institution's ability to deliver the treatment plan.

Imaging and Radiation Oncology Core in Houston has a collection of site-specific anthropomorphic phantoms. These anatomical regions include: H&N, pelvis, brain, thorax, spine, and liver. The H&N phantom is IROC-Houston's oldest and most common phantom used in the credentialing process. This custom phantom is constructed using a solid, high impact polystyrene slab that is fitted into an anthropomorphic shaped human head.^{10,11} The custom insert contains an acrylic spinal cord, and two (primary and secondary) PTVs manufactured using solid water which are dosimetrically monitored with radiochromic film and thermoluminescent detectors (TLDs).¹⁰ The spinal cord is adjacent to the primary PTV which requires each institution to create an IMRT plan with a steep dose gradient.

Integrating an MR imager within a radiotherapy system will inherently transform how treatment plans and deliveries are performed. Conventional IROC-Houston phantoms, designed for CT-only workflows, are not suited for MRIGRT workflows since the internal targets are not visible in MR.¹² This is because the lack of MR signal in IROC-Houston's traditional H&N phantom created a solid black MR image thus causing the internal structures to be indistinguishable. In order to use a H&N phantom to accommodate all potential MRIGRT workflows (i.e., CT/MR or MR-only workflows), it was critical that the phantom be tissue equivalent and visible in both CT and MR.

Several studies have attempted to manufacture phantoms that are MR and CT compatible, but these do not fit IROC-Houston's requirements.^{8,13–19} These requirements include that: (a) materials are dosimetrically equivalent to tissue, (b) materials are MR/CT visible, (c) portable radiation dosimeters are easily installed, (d) the phantom insert must be durable, and (e) the phantom requires minimal maintenance (e.g., can be stored at room temperature). The studies that have attempted to make MR and CT compatible phantoms used materials that either had short shelf lives, required additional additives to prevent micro-organism

infestation or required special storage conditions (i.e., refrigerators).^{13,14} Some studies attempted to construct a dual MR/CT H&N phantom by adding MR visible markers to phantoms that are traditionally used in CT-only work-flow.^{15,16} Other MR/CT compatible H&N phantoms were simplistic and were designed to address different challenges in MR-only workflows.¹⁷ These phantoms were not designed to perform end-to-end tests, but instead they were designed to quantify MR distortion and study the ability to create synthetic electron density from a MR image. Other studies have attempted to make multimodality phantoms by using silicone-based materials.^{18,19} Silicone has a higher atomic number ($Z = 13$) than soft tissue's effective atomic number ($Z_{\text{eff}} = 7.4$). The higher atomic number in silicone-based materials was found to be dosimetrically nonequivalent to solid water in the Steinmann et al. 2018 study.¹² There are commercially available multimodality H&N phantoms such as the CIRS STEEV phantom (CIRS, Norfolk, VA, USA) and Lucy three-dimensional QA phantom (Standard Imaging, Middleton, WI, USA). These phantoms provide contrast between tumor and surrounding materials by combining water with an MR contrast agent (e.g., manganese chloride or a gadolinium solution). Similarly to silicone-based materials, the high atomic number in these MR contrast agents will not dosimetrically represent soft tissue. Therefore, there is not an end-to-end MRIGRT H&N phantom that satisfies IROC-Houston's criteria to have portable dosimeters inside complex multicontrast internal structures that dosimetrically mimic soft tissue.

The aim of this study was to design, manufacture, and evaluate a tissue equivalent MR/CT visible anthropomorphic H&N phantom, that met IROC-Houston's phantom requirements and could be used as a QA tool to credential MRIGRT systems participating in NCI-sponsored NCTN clinical trials.

2. MATERIALS AND METHODS

The MRIGRT H&N phantom was designed to meet IROC-Houston's requirements such that this phantom could be used as an end-to-end QA metric for MRIGRT workflow and required minimal phantom maintenance. Gel-based materials used in the MRIGRT H&N phantom (Clear Ballistic Gel #20 and Superflab) were carefully selected based on findings in the Steinmann et al. 2018 study.¹² In short, the Steinmann *et al*/study characterized materials based on imaging, dosimetric, and physical characteristics. Materials which had high melting points, did not use preservatives or did not require special storage were included in that study. Materials recommended for MR/CT QA phantoms were tissue equivalent on CT (i.e., had comparable HU), were visibly distinguishable between water in both T1- and T2-weighted images and had comparable PDD curves as their respective organ sites.

The entire phantom was designed to represent humanoid structures (i.e., spinal cord, soft tissue) by using materials that were radiologically tissue equivalent in CT images, yet, had structures that were visibly differentiable in both MR and CT imagers. To minimize phantom maintenance, the gel-based MR/CT visible materials were enclosed in an airtight removable insert. Once the H&N insert was constructed, dosimetric reproducibility was measured using a 1.5 T Unity system and then sent out to three institutions to conduct a miniature end-to-end feasibility study. The feasibility study was used for the multi-

institutional dosimetric evaluation and for qualitatively examining the phantom's integrity after shipping to multiple locations.

2.A. Phantom design

The MRIGRT H&N phantom consisted of a water-fillable acrylic shell (The Phantom Laboratory, Salem, New York, USA) and a custom designed two-piece H&N insert visible in both CT and MR systems. Externally the hollow acrylic shell was morphed to resemble a human head, but internally it consisted of a rectangular concavity that tightly held the H&N insert shown in Fig. 1. The custom H&N insert was designed based on a Radiation Therapy Oncology Group (RTOG) oropharyngeal protocol (H-0022) which consisted of two PTVs (primary and secondary) and an OAR.¹⁰

Figure 2 displays the MRIGRT H&N insert. Internally, the insert consists of: (a) a moon-shaped cylindrical primary PTV, (b) a cylindrical secondary PTV, and (c) a cylindrical spinal cord-like structure that simulated an OAR. The primary PTV is adjacent to the OAR and the secondary PTV is located at a distance. Inferior and superior pieces of the two-part insert were secured together using two high impact polystyrene plastic screws. The MRIGRT H&N insert used radiochromic EBT3 film and double-loaded TLDs as portable dosimeters. At the insert's center, eight double-loaded TLD capsules were placed into the insert. Half of the TLDs were inserted into the inferior portion and, the other half were inserted in the same position on the superior piece. A total of three radiochromic films were placed into the insert to capture axial and sagittal planes. A sagittal film was placed through the primary PTV and OAR for each of the superior and inferior piece and an axial film was inserted in between the two pieces. Radiochromic films were pinpricked on the outer perimeters to allow for film registration. The purpose of the small pinpricked areas was to identify the film's location relative to the phantom's location. Compared to IROC-Houston's conventional H&N phantom, the MRIGRT H&N insert was designed with wider exterior walls with small pin holes which were used to record spatial alignment.

Clear Ballistic Gel #20 (Clear Ballistics, Fort Smith, Arkansas, USA) was used to create the PTV structures. The primary and secondary PTV had dimensions of 5.0 cm in length (superior–inferior direction) and had diameters of 4.0 and 2.0 cm, respectively. The primary PTV held a total of four TLDs (two central, and one each anterior and posterior from the center), while the secondary PTV held two TLDs (both central). The OAR was constructed using acrylic (Professional Plastics, Fullerton, CA, USA) which extended 13 cm in length and was 1 cm in diameter. The OAR held a total of two TLDs. Each TLD was located in the center of the spinal cord structure in each insert piece. Table I summarizes the materials used in each structure as well as the dimensions and total TLDs used. All structures were surrounded by melted Superflab that was encapsulated in solid water to create a rigid rectangular structure. Both Superflab and Clear Ballistic Gel #20 were melted at 121.1°C and 148.9°C, respectively, then poured into a solid water mold. The molds were moved to a vacuum chamber until the melted materials had solidified at room temperature. The airtight vacuum chamber was used to reduce air bubbles created during the pouring process and the molds were used to create precise and reproducible structures. To increase rigidity and to

sustain shape during rough shipping conditions, solid water was used to encapsulate internal structures and to create an exterior insert shell.

2.B. Phantom imaging

The MRIGRT H&N phantom was imaged on a CT simulator, MRIdian ⁶⁰Co, MRIdian Linac, and Unity system. The phantom was first scanned using a brain protocol on a GE Lightspeed CT simulator (General Electric Company, New York, NY, USA) with scanning parameters of: DFOV = 500.0 mm, 120 kVp, 275 mA, and slice thickness = 3 mm, pixel spacing 0.98 mm × 9 0.98 mm. Table II summarizes the MR scanning parameters on both the MRIdian and Unity systems.

2.C. Dose prescription

The prescription dose was based on the dosimetric requirements set for IROC-Houston's conventional H&N phantom. The dosimetric criteria are illustrated in Table III.

2.D. Treatment delivery

The MRIGRT H&N phantom was evaluated based on an end-to-end test for both reproducibility and feasibility studies using the TLD and EBT3 radiation dosimeters. During the reproducibility study, the MRIGRT H&N phantom was irradiated three times on a single Unity system. A multi-institutional feasibility study was then conducted by a dosimetric comparison of irradiations performed at three other MRIGRT sites. For this feasibility study, the phantom was irradiated using two different MRIdian ⁶⁰Co systems and was irradiated once on an MRIdian Linac system.

Thermoluminescent detectors were read in-house using the same method as IROC-Houston's off-site auditing program.²⁰ Double-loaded TLDs (ThermoFisher Scientific, Waltham, Massachusetts, USA) were used as an absolute dosimeter and were read 2 weeks from the irradiation date to account for fading. The exact amount of lithium fluoride powder inside a double-loaded TLD capsule was weighed using a Mettler AT261 DeltaRange (Mettler Toledo, Greifensee, Switzerland) scale and light output was measured using the Harshaw M3500 TLD reader (ThermoFisher Scientific, Waltham, Massachusetts, USA). The optical density from the irradiated film was read using a photoelectron CCD micro-densitometer (Photoelectron Corporation, North Billerica, MA, USA). The measured intensity read on the CCD micro-densitometer was converted to dose (via IROC-Houston's film calibration curve created for each film batch) and was postprocessed using an in-house MATLAB software (The MathWorks, Inc., Natick, MA, USA).²¹

Treatment delivery was compared to the expected TPS calculation and was analyzed by two methods: (a) comparing the reported to measured dose for each TLD location and (b) performing gamma analysis on axial and sagittal films and generating dose profiles for each orientation. Expected dose values on the Unity system were calculated using the Monaco TPS (research version 5.19.02; Elekta, Crawley, UK) whereas expected dose values on either MRIdian ⁶⁰Co or MRIdian Linac system were calculated using ViewRay System Treatment Planning and Delivery Software (VR-TPDS v. 5.4.1).

2.D.1. Reproducibility—The phantom was filled with water and imaged on a GE Lightspeed CT simulator. The CT images were transferred to Monaco TPS where TLDs, OAR, and PTVs were contoured and an IMRT plan was created. The IMRT treatment plan used nine gantry angles and used IMRT constraints similar to Tonigan's thesis using a median complexity treatment plan (i.e., creating a plan that provided adequate target coverage while creating steep dose gradients to spare the spinal cord).²²

The MRIGRT H&N phantom was positioned on the Unity system's couch and a uniform foam coil was placed above the phantom. The MR coil was specially designed for the Unity system such that the MR coil minimally attenuated the beam and would attenuate the beam uniformly.²³ Figure 3 displays the treatment setup used for the reproducibility study. Unlike MRIdian systems, the Unity system was not equipped with lasers inside the vault (i.e., no MR scanning lasers or wall-mounted lasers). In fact, the Unity system solely relied on capturing an MR image to account for any setup discrepancies between each irradiation. Part of the Unity system's workflow required a re-optimization based on the current setup position. The reproducibility test encompassed all parts of the workflow including MR setup verification methods. All irradiations for the reproducibility study were performed back-to-back on a single day using a single MRIGRT Unity system. During each irradiation the treatment couch was moved outside the bore and the insert was removed from the phantom to load new unirradiated detectors into the insert. Once unirradiated TLDs and film sheets were reloaded into the phantom, the H&N insert was screwed into the phantom and the treatment couch was moved back inside the bore. During this process, the phantom could have been moved to a slightly different position due to the couch movement and the insert's re-installation into the phantom. There were no lasers to verify whether the phantom was in the same position as the previous irradiation. To account for any movement, MR images were acquired before each irradiation and the treatment plan was re-optimized accordingly. Once the T1-weighted MR image was acquired, it was fused to the original CT image using Monaco's automatic image fusion tool. The automatic image fusion tool used the phantom's external shell to fuse the two images together. The primary and secondary PTV targets were used to verify that the two images were correctly registered. The fused image data set was used to re-optimize the dose distribution based on the phantom's current position.

The re-optimization used the original dose constraints and gantry positions to design the modified MLC positions according to the current anatomical positions captured from the MR. The optimization was performed using a fluence map with a structure-based cost objective function setting in Monaco's treatment planning software. The adjusted plan was accepted and was used to treat the MRIGRT H&N phantom. The mean doses in the TPS were recorded at all TLD locations and were used to compare with the measured TLD readings. For each irradiation, the total treatment took around 35 min and reloading the phantom with new detectors took around 15 min. The total treatment time included capturing an MR image before each irradiation and delivering a highly modulated step-and-shoot IMRT plan. The MRIGRT H&N treatment plan was exported and was then used to compare the measured and predicted TPS doses.

2.D.2. Feasibility study—During the feasibility study, the phantom was irradiated on either an MRIdian ⁶⁰Co or an MRIdian Linac system and was planned using ViewRay's own

treatment planning software. Each institution received detailed instructions which helped to create uniformity between the participating institutions. These instructions required the institutions to: (a) prepare the phantom for imaging and treatment (i.e., fill the hollow phantom with tap water and place the insert into the phantom), (b) capture a CT-simulated image, (c) contour the organs and design an IMRT treatment plan, (d) verify treatment setup by capturing an on-board MR image, and (e) deliver the expected IMRT treatment plan. Each institution was also instructed to contour the TLD capsules and record the TLD's expected minimum, maximum, and mean dose. The digital treatment plan data were sent to IROC-Houston for evaluation.

3. RESULTS

3.A. Phantom imaging

As shown in Fig. 4, the MRIGRT H&N phantom was imaged using a GE CT simulator, Unity and MRIdian MRIGRT systems. All four images in Fig. 4 clearly display distinguishable internal structures. This ability to see contrast between the disease site and surrounding tissue allows institutions to real-time visualize the phantom during treatment. The insert's rigid exterior and OAR are made of solid water and acrylic, respectively. These materials lack hydrogen content and appear black on the MR image. The OAR is visualized through the contrast between the absence of signal surrounded by MR-visible surrounding tissue. In comparison to the MRIdian Linac and MRIdian ^{60}Co systems, the Unity system captures a higher signal-to-noise ratio (SNR) image. The MRIGRT systems also show different contrasts within the insert. These variations in contrast and higher SNR are attributed to the different MR scanning sequences and magnetic fields, respectively. A T1-weighted imaging sequence was applied to the 1.5 T Unity system whereas a TrueFISP sequence was applied to the 0.35 T MRIdian system. Pouring melted Superflab into a mold inherently caused small air pockets. These tiny air pockets in the melted Superflab were not visible on CT but created circular black artifacts in the MR images. There are two likely potential contributors to why air pockets are visible on the Unity system (and not on others) which are: (a) superior resolution and (b) greater susceptibility in the Unity's MR sequence. The void signal from the air bubbles are visible on the Unity system due to a higher spatial resolution MR image. The air bubbles are not visible on the MRIdian system nor on the CT image due to lower spatial resolution. The air bubbles could have also caused a greater image distortion in the Unity system simply due to the scanning sequence and magnetic field used. Using a gradient echo sequence and a higher magnetic field could have caused greater susceptibility artifacts visible in the Unity image but not captured in the MRIdian system.

3.B. Treatment delivery

Thermoluminescent detectors results were evaluated on the same passing criteria that IROC-Houston uses to credential institutions; thus, TLDs that were within 7% (i.e., 0.93 to 1.07) of the reported dose were considered to be within IROC-Houston's standard acceptance criteria. Tables IV and V show the average ratio between measured and reported TLD values in the reproducibility and feasibility studies, all of which passed IROC-Houston's passing criteria. For the Unity system, the average of the three measurements varied from 0.94 to 0.98 for the different PTV locations; the average ratio over all locations was 0.96. For the

ViewRay systems, the ratio of measured to reported doses was higher, with an overall average of 1.00. The PTVs in the posterior locations are potentially expected to have greater discrepancies due to the steep dose gradient, which are consistent with findings in IROC-Houston's conventional H&N phantom.

Axial and sagittal films were evaluated using a gamma analysis and used the same standard film analysis process that IROC-Houston uses for the conventional H&N phantom.²⁴ Films were said to pass if more than 85% of the pixels passed a global dose of 7% and a 4-mm distance to agreement (DTA) criterion. Like IROC-Houston standard film analysis process, there was not a dose threshold to eliminate any low-dose pixels but the films were masked at the edges to prevent gamma analysis at those edge locations. Tables VI and VII display the percentage of pixels passing the gamma criterion for axial and sagittal film planes in the reproducibility and feasibility study, respectively. The average percent of pixels passing in the reproducibility study were 97.8% and 89.7% for axial and sagittal film planes, respectively. In the feasibility study, all axial and sagittal films passed IROC-Houston's gamma criteria with an average pixel passing of 97.3% and 96.2%, respectively. During the gamma analysis three dose profiles were generated in anterior–posterior, left–right, and superior–inferior orientation. The typical dose profiles generated from these studies are shown in Fig. 5. From a qualitative perspective, film dose profiles and calculated dose profiles were in good agreement with all studies.²⁵

4. DISCUSSION

The MRIgRT H&N insert was constructed from gel-based materials. Since these materials were gel-based, they had more MR contrast than solid materials which allowed them to be visible in MR. To the authors knowledge, Superflab and Clear Ballistic Gel #20 have not been used to construct an MR visible phantom. In fact, most MR phantoms contain water that is doped with gadolinium. Gadolinium contrast was not used in this study since it has a higher atomic number than soft tissue and would not be dosimetrically equivalent.

IROC-Houston is responsible for ensuring multiple institutions are delivering consistent treatments. One method by which IROC-Houston evaluates this consistency is by sending anthropomorphic phantoms with detailed dose prescription instructions to institutions. With the goal of using the MRIgRT H&N phantom to examine an institution's ability to deliver radiation consistently with other institutions, it was important that this phantom also use the same instructions and evaluation metrics as IROC-Houston's conventional H&N phantom. Additionally, IROC-Houston allowed institutions to use other MR workflow components as needed. Thus, institutions were free to incorporate MR-based treatment planning and MR image guidance since this phantom was designed to accommodate either MR/CT workflows or MR-only workflows. While most institutions used CT-only to create an IMRT plan, one institution (ViewRay 4) chose to use the electron density captured on a CT image and then plan based on the MR image.

While the primary goal of this study was to determine the feasibility of using this dual MR/CT visible phantom as an end-to-end test, a secondary goal was to qualitatively examine the robustness of the phantom. With the MRIgRT H&N phantom being shipped to multiple

institutions, it was critical that the phantom could withstand harsh mechanical stress (e.g., in-transit drops and vibrations). The phantom's robustness was determined by visually inspecting each component of the phantom (e.g., shell and phantom insert) to see if there were any signs of cracks or material degradation after each shipment back to IROC-Houston. While there could have been additional stress tests, the visual inspection was consistent with IROC-Houston's current workflow and how previous phantoms were commissioned. The MRIGRT H&N did not show signs of cracks or mechanical stress from shipping the phantom; thus, suggesting that the MRIGRT H&N phantom was robust enough to ship to multiple institutions.

Thermoluminescent detectors ratios consistently were lower in the reproducibility test than in the feasibility test, which was mostly attributed to the treatment planning software. The reproducibility test was planned using Monaco, whereas all the institutions in the feasibility tested used VRTADS. At the time of this work, Monaco's research treatment planning software did not fully model the beam configuration (i.e., surface coil) in the Unity system. Specifically, this Monaco TPS version did not account for the surface coil, but it did account for the entire cryostat and body coil. While a clinical version will account for the surface coil prior to human treatments, this was not available at the time of the study. Not modeling the surface coil in the research model contributed to higher differences between measured-to-expected doses. Using a PTW 30013 ionization chamber, Hoogcarstel et al found that the surface coil attenuated an incident beam by as much as 2.2%.²³ Additionally, IROC-Houston's initial TLD reading uncertainty is 2.3%.²⁶ The maximum attenuation discrepancy found by Hoogcarstel et al. and the initial TLD reading uncertainty was contributing factors in the dose discrepancy between the treatment planning system and TLD measurements. Excluding differences due to treatment planning software, the results from the reproducibility test showed the predicted and measured doses were consistent. This consistency was indicated by having <1.5% coefficient of variation between irradiations.

Thermoluminescent detectors ratios between measured readings to the institution reported dose using the MRIGRT H&N phantom were compared to TLD ratios of the conventional H&N phantom described in Molineu et al. 2013. The percent difference between the average TLD ratio on the conventional H&N to the MRIGRT H&N phantom in the primary PTV and secondary PTV were shown to be 1.18%, and 0.03%, respectively. This demonstrates that the MRIGRT has similar results expected as the conventional H&N phantom and suggests that it is as capable as the CT-only phantom. While the study size is small due to the limited number of MRIGRT systems currently in the United States, this further emphasizes that the MRIGRT H&N phantom could be an appropriate tool for credentialing multi-institutional clinical trials.

The purpose of this work was to develop an end-to-end QA phantom which IROC-Houston could use to credential MRIGRT systems wishing to participate in NCI-sponsored clinical trials. Therefore, it was critical that the MRIGRT H&N phantom used the same consistent passing criteria as IROC-Houston's conventional H&N phantom for both feasibility and reproducibility studies. The passing criteria for IROC-Houston's conventional H&N phantom and for this study were 7%/ 4 mm with at least 85% of the pixels passing gamma analysis. All the studies passed IROC-Houston's H&N passing criteria in the four MRIGRT

systems (three ViewRay MRIGRT units in the feasibility study and one Unity MRIGRT system in the reproducibility study). These results demonstrated that the MRIGRT H&N phantom is potentially an effective credentialing end-to-end QA tool for MRIGRT systems.

Each step in the radiation treatment process will have associated uncertainties. Since MRIGRT systems have different workflows than conventional linear accelerators, they will also have different associated uncertainties. Some of the various sources of uncertainties could arise from: (a) MR/CT image fusion, (b) potential minor dosimetric effects on TLDs from an MR environment, (c) linear accelerator output consistency (d) MR geometrical accuracy, and (e) re-optimization differences.²⁷ Wang et al. 2018 quantify the image quality on the Unity system (1.5 T) and measured the geometric distortion to be within 0.5 mm in both axial and sagittal planes using a large ACR MRI phantom (diameter = 20.32 cm and length = 12.34 cm).²⁸ While the major purpose of these studies was not to quantify the source of uncertainties, our studies were used to evaluate an institution's performance based on the entire treatment process. If an institution failed IROC-Houston's passing criterion then it was that institution's responsibility to further investigate the source of errors and implement new protocols to mitigate uncertainties from those components. Even with various uncertainties, the gamma results from the MRIGRT H&N phantom demonstrated that those uncertainties played an acceptable role in the overall dose delivery.

5. CONCLUSIONS

National Cancer Institute-sponsored clinical trials will further investigate the impact of using MRIGRT systems for various disease sites including cancers in the H&N region. The MRIGRT H&N phantom was designed to credential institutions wishing to use IMRT techniques with MRIGRT systems. This phantom was designed to be used in all aspects of MRIGRT treatment workflows in that it was constructed using tissue equivalent materials which could be visualized in 0.35 T–1.5 T MR imagers, and in CT imagers. The MRIGRT H&N phantom shows a promising useful credentialing tool since the results from the four MRIGRT systems all passed IROC-Houston's conventional H&N acceptability criteria.

ACKNOWLEDGMENTS

This work was supported by Public Health Service Grant U24 CA180803 and R01CA218148 awarded by the National Cancer Institute, United States Department of Health and Human Services. Additionally, this research is supported by the Andrew Sabin Family Foundation; Dr. Fuller is a Sabin Family Foundation Fellow.

REFERENCES

1. Mutic S, Dempsey JF. The ViewRay system: magnetic resonance-guided and controlled radiotherapy. *Semin Radiat Oncol.* 2014;24:196–199. [PubMed: 24931092]
2. ViewRay. MRIdian Linac Advantage In. L-0083 RevE ed. Oakwood Village, OH; 2017.
3. ViewRay. The MRIdian Advantage In. L-0013 Rev. D10/2015 ed Oakwood Village, OH; 2015.
4. Lagendijk JJ, Raaymakers BW, Raaijmakers AJ, et al. MRI/linac integration. *Radiother Oncol.* 2008;86:25–29. [PubMed: 18023488]
5. Raaymakers B, Lagendijk J, Overweg J, et al. Integrating a 1.5 T MRI scanner with a 6 MV accelerator: proof of concept. *Phys Med Biol.* 2009;54:N229. [PubMed: 19451689]

6. Raaymakers B, Jürgenliemk-Schulz I, Bol G, et al. First patients treated with a 1.5 T MRI-Linac: clinical proof of concept of a high-precision, high-field MRI guided radiotherapy treatment. *Phys Med Biol.* 2017;62: L41. [PubMed: 29135471]
7. Bruijnen T, Stemkens B, Terhaard C, Lagendijk J, Raaijmakers C, Tjissen R. MRI-based radiation therapy: intrafraction motion quantification of head and neck tumors using cine magnetic resonance imaging. *Int J Radiat Oncol Biol Phys.* 2018;100:1358.
8. Khoo VS, Dearnaley DP, Finnigan DJ, Padhani A, Tanner SF, Leach MO. Magnetic resonance imaging (MRI): considerations and applications in radiotherapy treatment planning. *Radiother Oncol.* 1997;42:1–15. [PubMed: 9132820]
9. Followill D, Ibbott G, Molineu A, Alvarez P, Hernandez N. Credentialing for advanced technology clinical trials using anthropomorphic phantoms. In: Vienna, Austria: IAEA; 2006 https://inis.iaea.org/collection/NCLCollectionStore/_Public/38/002/38002530.pdf#page=452
10. Molineu A, Hernandez N, Nguyen T, Ibbott G, Followill D. Credentialing results from IMRT irradiations of an anthropomorphic head and neck phantom. *Med Phys.* 2013;40:022101. [PubMed: 23387762]
11. Molineu A, Followill DS, Balter PA, et al. Design and implementation of an anthropomorphic quality assurance phantom for intensity-modulated radiation therapy for the Radiation Therapy Oncology Group. *Int J Radiat Oncol Biol Phys.* 2005;63:577–583. [PubMed: 16168849]
12. Steinmann A, Stafford RJ, Sawakuchi G, et al. Developing and characterizing MR/CT-visible materials used in QA phantoms for MRgRT systems. *Med Phys.* 2018;45:773–782. [PubMed: 29178486]
13. Gallas RR, emohr H, ün N, Runz A, Niebuhr NI, Jäkel O, Greilich S. An anthropomorphic multimodality (CT/MRI) head phantom prototype for end-to-end tests in ion radiotherapy. *Zeitschrift fuer Medizinische Physik.* 2015;25:391–399.
14. Soliman AS, Burns L, Owraing A, et al. A realistic phantom for validating MRI-based synthetic CT images of the human skull. *Med Phys.* 2017;44:4687–4694. [PubMed: 28644905]
15. Cunningham J, Glide-Hurst C. End-to-end phantom evaluation for transition from MR/CT combined to MR-only workflow: SU-I-GPD-J-84. *Med Phys.* 2017;44:2818.
16. Hoogcarpsel S, Kerkmeijer L, Lagendijk J, Van Vulpen M, Raaymakers B. SU-F-J- 150: development of an end-to-end chain test for the first-in-man MR-guided treatments with the MRI linear accelerator by using the alderman phantom. *Med Phys.* 2016;43:3442.
17. Price RG, Kim JP, Zheng W, Chetty IJ, Glide-Hurst C. Image guided radiation therapy using synthetic computed tomography images in brain cancer. *Int J Radiat Oncol Biol Phys.* 2016;95:1281–1289. [PubMed: 27209500]
18. Niebuhr NI, Johnen W, Echner G, et al. The ADAM-pelvis phantom-an anthropomorphic, deformable and multimodal phantom for MRgRT. *Phys Med Biol.* 2019;64:04NT05.
19. Cunningham JM, Barberi EA, Miller J, Kim JP, Glide-Hurst CK. Development and evaluation of a novel MR-compatible pelvic end-to-end phantom. *J Appl Clin Med Phys.* 2019;20:265–275. [PubMed: 30411477]
20. Kirby T, Hanson W, Johnston D. Uncertainty analysis of absorbed dose calculations from thermoluminescence dosimeters. *Med Phys.* 1992;19:1427–1433. [PubMed: 1461205]
21. Repchak R Evaluation of the Effectiveness of Anisotropic Analytical Algorithm in Flattened and Flattening-Filter-Free Beams for High Energy Lung Dose Delivery using the Radiological Physics Center Lung Phantom. Houston, TX: The University of Texas M.D. Anderson Cancer Center; 2012.
22. Tonigan J Evaluation of Intensity Modulated Radiation Therapy (IMRT) Delivery Error Due to IMRT Treatment Plan Complexity and Improperly Matched Dosimetry Data. Houston, TX: Graduate School of Biomedical Sciences, The University of Texas M. D. Anderson Cancer Center; 2011.
23. Hoogcarpsel SJ, Zijlema SE, Tjissen RH, et al. Characterization of the first RF coil dedicated to 1.5 T MR guided radiotherapy. *Phys Med Biol.* 2018;63:025014. [PubMed: 29260729]
24. Low DA, Harms WB, Mutic S, Purdy JA. A technique for the quantitative evaluation of dose distributions. *Med Phys.* 1998;25:656–661. [PubMed: 9608475]

25. Carson ME, Molineu A, Taylor PA, Followill DS, Stingo FC, Kry SF. Examining credentialing criteria and poor performance indicators for IROC Houston's anthropomorphic head and neck phantom. *Med Phys.* 2016;43:6491–6496. [PubMed: 27908168]
26. Kry SF. *The Clinical Use of Luminescent Dosimeters*; 2018.
27. Steinmann A, O'Brien D, Stafford R, et al. Investigation of TLD and EBT 3 performance under the presence of 1.5 T, 0.35 T, and 0T magnetic field strengths in MR/CT visible materials. *Med Phys.* 2019;46:3217–3226. [PubMed: 30950071]
28. Wang J, Yung J, Kadbi M, Hwang K, Ding Y, Ibbott GS. Assessment of image quality and scatter and leakage radiation of an integrated MRLINAC system. *Med Phys.* 2018;45:1204–1209. [PubMed: 29363770]

FIG. 1.

The magnetic resonance imaging guided radiotherapy H&N Phantom. The phantom consists of a water-fillable anthropomorphic shell and a removable 7.5 cm × 10.5 cm × 13 cm MR/computed tomography compatible two-piece insert. Two white polystyrene screws are used to connect the two pieces to form a single insert which then attaches into the water-fillable shell.

FIG. 2.

The magnetic resonance imaging guided radiotherapy (MRIgRT) H&N insert. (a) An axial film was placed in between the two piece insert, and two films were used to capture a sagittal plane by placing one piece of film in between the sagittal film insert for each piece. (b) An axial computed tomography slice with the MRIgRT insert labeled.

FIG. 3.

The magnetic resonance imaging guided radiotherapy (MRIGRT) H&N insert. (a) An axial film was placed in between the two piece insert, and two films were used to capture a sagittal plane by placing one piece of film in between the sagittal film insert for each piece. (b) An axial computed tomography slice with the MRIGRT insert labeled.

FIG. 4.

The magnetic resonance imaging guided radiotherapy (MRIGRT) H&N phantom was filled with water and scanned on: GE computed tomography simulator, Unity system's 1.5 T MRI with a T1 sequence, and a TrueFISP sequence for both ViewRay's MRIdian Linac and ViewRay's MRIdian Co-60 0.35 T systems. All images clearly show the organ at risk, primary and secondary planning target volume.

FIG. 5.

Dose profiles generated in the (top) anterior–posterior, (middle) left–right, and (bottom) superior–inferior direction. These graphs compare dose profiles generated on film to those generated from the treatment planning. These graphs were generated from institution 3, but resemble the typical dose profiles generated from both feasibility and reproducibility studies. (Additionally, similar profile agreements are commonly found in passing IROC-Houston’s conventional H&N phantoms.) In general these profiles show good agreement from the TPS and measured films, although the anterior–posterior profile shows a sub-cm shift which is more visible in the steep dose gradient region. This 0.16 cm shift could have occurred due to

a user failing not to shift after acquiring a magnetic resonance image on a 0.35 T MRIdian ^{60}Co system.²⁵

Author Manuscript

Author Manuscript

Author Manuscript

Author Manuscript

Table I.

The materials used to manufacture a magnetic resonance imaging guided radiotherapy (MRIGRT) H&N insert, dimensions of each and total number of thermoluminescent detectors (TLDs) used in each structure (*half of the TLDs were inserted into the inferior part and the other half inserted into the superior part of the MRIGRT H&N insert).

Structure	Material	Diameter (cm)	Length (cm)	Total TLDs used*
Primary PTV	Clear Ballistic Gel #20 ^a	4	5	4
Secondary PTV	Clear Ballistic Gel #20 ^a	2	5	2
OAR	Acrylic ^b	1	13	2

OAR, organ at risk; PTV, planning target volume.

^aClear Ballistics, Fort Smith, Arkansas, USA.

^bProfessional Plastics, Fullerton, California, USA.

Table II.

Magnetic resonance (MR) images were captured on both MRIdian and Unity systems. The MRIdian systems acquired a true fast imaging with steady-state free precession (TrueFISP) image and the Unity system acquired a T1-weighted.

Parameters	MRIdian Linac	MRIdian Co-60	Unity
MR scanning sequence	True fast imaging with steady-state free precession (TrueFISP) *	True fast imaging with steady-state free precession (TrueFISP) *	T1-weighted gradient
Flip angle (FA)	60°	60°	8°
Repetition time (TR)	3.00 ms	3.33 ms	8.0 ms
Echo time (TE)	1.43 ms	1.43 ms	3.6 ms
Echo train length (ETL)	–	–	136
Number of excitations (NEX)	1	1	1
Acquisition matrix	300 mm × 340 mm	266 mm × 266 mm	384 mm × 384 mm
Slice thickness	1.5 mm	3.0 mm	2.2 mm
Acquisition time	23 s	25 s	4 min
Pixel spacing	1.49 mm × 1.49 mm	1.50 mm × 1.50 mm	0.70 mm × 0.70 mm

* TrueFISP is currently the only MR imaging sequence that MRIdian Co-60 and MRIdian Linacs acquire.

Table III.

During both reproducibility and feasibility studies, treatment plans were based on the same dose constraints.

MRIGRT H&N structure	Dose prescription
Primary PTV	D ₉₅ 6.6 Gy
	D ₉₉ 6.1 Gy
Secondary PTV	D ₉₅ 5.4 Gy
	D ₉₉ 5.0 Gy
OAR	D _{Max} < 4.5 Gy
Normal tissue	D _{Max} 7.3 Gy

MRIGRT, magnetic resonance imaging guided radiotherapy; OAR, organ at risk; PTV, planning target volume.

Table IV.

Reproducibility results of four TLD positions in the primary planning target volume (PTV) and the two TLD positions in the secondary PTV. The top row represents TLD locations. Each row represents the ratio between measured TLD and calculated dose from Monaco's treatment planning software for each irradiation. The second to last row represents the average ratio between measured and calculated dose, and the final row represents the coefficient of variance. The TLD measurements were all within 6% of the reported TLD dose.

Reproducibility test	PTV superior anterior	PTV inferior anterior	PTV superior posterior	PTV inferior posterior	Secondary PTV: superior	Secondary PTV: inferior
Unity 1-a	0.97	0.97	0.94	0.94	0.97	0.96
Unity 1-b	0.98	0.95	0.94	0.95	0.95	0.95
Unity 1-c	0.98	0.96	0.94	0.94	0.96	0.96
Average	0.98	0.96	0.94	0.95	0.96	0.96
Coefficient of variance	0.7%	1.5%	0.4%	0.9%	1.1%	0.4%

Table V.

Feasibility study results for four TLD positions in the primary planning target volume (PTV) and two TLD positions in the secondary PTV. Each row represents the ratio between measured TLD and calculated dose from Monaco's treatment planning software for each irradiation. The results are the ratio between measured TLD dose and reported dose from the treatment planning software

Institution	Energy	PTV superior anterior	PTV inferior anterior	PTV superior posterior	PTV inferior posterior	Secondary PTV: superior	Secondary PTV: inferior
ViewRay 2	6 MV	1.01	1.01	1.02	1.00	1.00	1.00
ViewRay 3	Co-60	1.03	1.03	1.02	1.01	1.00	1.02
ViewRay 4	Co-60	0.98	0.97	0.95	0.99	0.97	0.99
Average	–	1.00	0.99	0.98	0.99	0.99	1.00

Table VI.

The magnetic resonance imaging guided radiotherapy H&N phantom was irradiated three times on a 1.5 T Unity magnetic resonance Linac system. Axial and sagittal planes were evaluated based on 7%/4 mm gamma criteria. The sagittal plane is located in-between the primary planning target volume and the organ at risk (OAR). The systematic lower percent of pixels passing in the sagittal plane is a consequence of having a steep dose gradient near the OAR.

Institution	Pixel passing ($\pm 7\%/4$ mm)	
	Axial (%)	Sagittal (%)
Unity 1-a	96.4	89.9
Unity 1-b	98.1	89.9
Unity 1-c	99.1	89.2
Average	97.8	89.7

Table VII.

Two different magnetic resonance imaging guided radiotherapy systems treatments were evaluated based on the 7% dose and 4-mm distance to agreement gamma criteria for both axial and sagittal planes. This table displays the percentage of pixels passing the gamma criteria. The systematic lower percent of pixels passing in the sagittal plane seen for the Unity system (Table VI) is not evident in the ViewRay results presented in Table VII; the source of this difference in the results has not been determined but may be due to statistical variation.

Institution	Energy	Pixel passing ($\pm 7\%/4$ mm)	
		Axial (%)	Sagittal (%)
ViewRay 2	6 MV	97.9	95.7
ViewRay 3	Co-60	96.7	96.6
Average	–	97.3	96.2

* Data unavailable from ViewRay 4 institution for analysis.