Design, development, and implementation of the Radiological Physics Center’s pelvis and thorax anthropomorphic quality assurance phantoms

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The Radiological Physics Center (RPC) developed two heterogeneous anthropomorphic quality assurance phantoms for use in verifying the accuracy of radiation delivery: one for intensity-modulated radiation therapy (IMRT) to the pelvis and the other for stereotactic body radiation therapy (SBRT) to the thorax. The purpose of this study was to describe the design and development of these two phantoms and to demonstrate the reproducibility of measurements generated with them. The phantoms were built to simulate actual patient anatomy. They are lightweight and water-fillable, and they contain imageable targets and organs at risk of radiation exposure that are of similar densities to their human counterparts. Dosimetry inserts accommodate radiochromic film for relative dosimetry and thermoluminescent dosimetry capsules for absolute dosimetry. As a part of the commissioning process, each phantom was imaged, treatment plans were developed, and radiation was delivered at least three times. Under these controlled irradiation conditions, the reproducibility of dose delivery to the target TLD in the pelvis and thorax phantoms was 3% and 0.5%, respectively. The reproducibility of radiation-field localization was less than 2.5 mm for both phantoms. Using these anthropomorphic phantoms, pelvic IMRT and thoracic SBRT radiation treatments can be verified with a high level of precision. These phantoms can be used to effectively credential institutions for participation in specific NCI-sponsored clinical trials © 2007 American Association of Physicists in Medicine. [DOI: 10.1118/1.2737158]

Key words: quality assurance, anthropomorphic phantoms

I. INTRODUCTION

The mission of the Radiological Physics Center (RPC), which was established in 1968, is to assure the National Cancer Center (NCI) and the Cooperative Study Group that institutions participating in NCI cooperative clinical trials deliver prescribed radiation doses that are clinically comparable and consistent. The RPC accomplishes this by assessing each institution’s radiation therapy programs through off-site, remote auditing and on-site dosimetry reviews. Mailable anthropomorphic quality assurance (QA) phantoms, an important part of the remote monitoring audits, are used to verify the accuracy of tumor-dose delivery for special treatment techniques, such as intensity-modulated radiation therapy (IMRT) and stereotactic body radiation therapy (SBRT). These phantoms are also used to credential institutions to participate in specific advanced-technology clinical trials. The RPC is the only QA group to provide such QA phantoms to verify the complete treatment process from imaging to treatment planning to dose delivery for institutions participating in clinical trials in North America.

QA for conventional therapy techniques and treatment-planning dose calculation is described in American Association of Physicists in Medicine Task Group reports 40 and 53.1,2 Unlike conventional radiation therapy, with IMRT it is difficult to assess individual dosimetry parameters to verify dose calculation or treatment delivery. IMRT treatment verification is unique in that although the dose distribution of individual beamlets can be accurately verified,3,4 the large number of beamlets used in IMRT limits the use of simple geometric patient-specific verifications.5 The dynamic nature of the delivery of IMRT further complicates QA measurement of IMRT dose distributions.6 Positioning uncertainties also complicate the analysis of discrepancies between single-point detector measurements and calculated doses. Treatment verification is a concern with all IMRT multileaf delivery modalities.

Treatment of the thorax also presents unique QA problems. Target motion and heterogeneities in the beam path complicate the delivery of dose to both target and normal tissues. Of particular concern is the accuracy of heterogeneity-corrected dose calculations from modern treatment-planning computers. Whether the algorithm is pencil-beam based, superposition convolution, or Clarkson-scatter corrected, dose calculations for the lungs should be verified in a clinically representative manner prior to clinical implementation and before use in clinical trials where consistency is of the utmost importance.

Patient treatment verifications typically measure the accuracy of the dose delivered as well as the spatial positioning of the dose distribution. These measurements are most often performed by delivering hypothetical and/or patient treatments to various simple geometry phantoms.5–16 For example, using the Corvus treatment planning system (TPS, Nomos Corporation, Sewickley, PA), one can recompute the...
dose distribution from optimized intensity profiles on a different computed tomography (CT) data set, usually a QA phantom. Simple homogeneous and heterogeneous spherical and cylindrical phantoms have also been used with ion chambers to monitor the delivered doses for multifield plans. Point-dose measurements using ion chambers or thermoluminescent dosimeters (TLDs) are limited to regions of low-dose gradient but complement film-measured relative-dose distributions.

Verification of the overall treatment procedure should include patient-image acquisition, treatment planning, and dose delivery. Therefore to verify the safety and accuracy of a complicated treatment delivery, the simple transfer of the dose distribution to a homogeneous cubic or cylindrical phantom or a hypothetical benchmark case may be inadequate. However, a phantom QA system that offers human-oid external shape, heterogeneities, targets, and critical structures will allow more complete evaluation of the overall treatment procedure. To this end, the RPC has developed and commissioned two anthropomorphic QA phantoms, a male pelvis and thorax, which are similar to the RPC head and neck phantom described previously. This report describes the design and development of each of these phantoms and demonstrates the reproducibility of measurements made with these phantoms under controlled irradiation conditions.

II. DESIGN OF THE RPC QA PHANTOMS

A. Phantom design

Two features of the RPC’s remote monitoring infrastructure were considered in the design of the two QA phantom systems. First, because the phantoms are mailed to institutions participating in clinical trials, they were designed to be lightweight and durable. The International Atomic Energy Agency’s (IAEA’s) pelvic dosimetric phantom, an oblong, water-fillable shell approximating the exterior shape of the abdomen, served as the initial model for our external phantom shells. The RPC QA pelvic phantom, which was designed to be more anthropomorphic than the IAEA phantom, includes heterogeneities, more organ structures, and film dosimeters. As well, the RPC QA phantoms approximate the size, shape, geometry, and heterogeneity of a patient’s anatomy and are designed to simulate realistic anatomic treatment challenges. Second, 3D treatment planning requires that the phantom be imageable on CT scans so that the target and critical structures can be identified and contoured. Our QA phantoms were constructed of materials that simulate patient tissue CT densities and patient geometry. In preparation for designing these phantoms, anatomic data and treatment plans for nine patients with prostate cancer and five with lung cancer were reviewed to determine the size, location, and CT density of the heart, spine, lung, prostate, bladder, rectum, and femoral head. These data were obtained by using the ADAC Pinnacle TPS (Elekta, Milpitas, CA) built-in measurement tools. Each phantom has cylindrical inserts that slide into the external shell and that contain imageable targets and organs at risk (OARs) and/or dosimeters. The insert and the outer shape and size of the phantoms were designed to reflect actual patient anatomy. Soft-tissue, bony, critical, and target structures, which are important in prostate IMRT and lung treatments, were identified and placed within the pelvic and lung phantoms to further simulate actual patient anatomy. Once the locations and densities of the structures were determined, a survey of several commercially available materials was conducted to find materials of a similar density and with a similar CT number as those of the patient prostate, lung, heart, spine, bladder, rectum, and femoral heads. Material samples were immersed in a tank of water and imaged with a GE Advantage CT scanner (GE Medical Systems, Waukesha, WI). Regions of interest were marked on the images of each material, and an average CT number for each material was calculated. Each phantom shell was designed to represent the size of the average patient and contained water to simulate all unit-density tissues.

1. Pelvis phantom design

The pelvis phantom is shown in Fig. 1. It is lightweight and water-fillable, and it has a PVC exterior shell that was designed to approximate the size and shape of an average patient. Within the phantom, the femoral heads are simulated by two bone-density polybutylene terephthalate (PBT)-polyester cylinders (Boedeker Plastics, Shiner, TX) that are mounted to the inferior plate of the phantom shell on the right and left sides of the holder for the imaging and dosimetry inserts. The femoral heads provide imaging and treatment heterogeneity within the phantom similar to that of an actual patient. Each femoral head has an acrylic insert that contains a single TLD capsule at the level of the target center for monitoring the absorbed dose to the femoral head. The asymmetrical positioning of the acrylic TLD holders within the femoral heads allows the treatment planner to identify the phantom left from right.

The inferior side of the pelvic phantom (Fig. 1) provides access to the inserts containing TLD and/or film. Acrylic rods, each of which hold a TLD capsule at the tip, are inserted into hollow acrylic tubes that are anchored to the other end of each phantom and extend through the center of the OARs to provide point-dose measurements. A large acrylic tube accepts either the imaging insert or the dosimetry insert.
These interchangeable inserts lock into place with an alignment notch located at the end of the tube in a unique orientation to ensure positioning reproducibility.

The imaging insert presented in Fig. 2 shows the prostate, bladder, and rectum structures mounted in the acrylic water-fillable shell. The imaging insert was designed to mimic patient anatomy and contains the target and OARs that are important in prostate treatments such as a spherical nylon ball to simulate the prostate, a polyethylene ball that cups the prostate and simulates the bladder, and a cylinder of wax enclosed in a thin polyethylene tube that represents the rectum and rectal wall. The materials selected for each component were of a similar density and CT number as shown in Table I. CT images of the imaging insert within the phantom shell provide anatomical information similar to actual patient anatomy for treatment planning purposes. A comparison of the phantom anatomy and representative patient anatomy as viewed in CT images is shown in Figs. 3 and 4. The geometry and placement of the phantom structures provide a treatment planning challenge similar to that presented by a patient.

The dosimetry insert replaces the imaging insert during treatment delivery. As shown in Fig. 5, the dosimetry insert is a solid cylinder of high-impact polystyrene. Like the imaging insert, an alignment notch is used to correctly and reproducibly place the insert in the phantom shell. To allow dosimeter loading, the insert has been constructed in two halves: inferior and superior. The two halves of the insert are held together with four nylon rods. The dosimetry insert holds two TLD capsules, each offset 3 mm from the target center. Radiochromic film is placed into the carefully machined film slots that intersect at the center of the target in the coronal and sagittal planes. The dosimetry insert contains four registration guide holes for marking films after they are loaded into the insert. The impression marks made from the registration holes help to secure the film in place and allow scanned films to be registered in phantom coordinates.

### 2. Thorax phantom design

The heterogeneous thorax phantom was designed in much the same way as the pelvic phantom. The phantom’s dimensions were determined from a sampling of patient cases to simulate an average patient. The phantom, shown in Fig. 6, consists of a PVC shell filled with water that contains a simulated heart made of nylon, a spine made of PBT-

![Fig. 2. Pelvis phantom imaging insert is a water-fillable acrylic shell containing a polyethylene bladder, nylon prostate, and wax rectum with polyethylene rectal wall. Bladder cups around the spherical prostate are also shown.](image)

![Fig. 3. Transverse axial CT scan of phantom (left) and patient (right). Phantom anatomy compares well with patient anatomy.](image)

<table>
<thead>
<tr>
<th>Phantom Structure</th>
<th>Material</th>
<th>Density (g/cm³)</th>
<th>CT Number Patient</th>
<th>CT Number Phantom</th>
</tr>
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<td>Rectum Polyethylene/wax</td>
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<td>1001</td>
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<td></td>
<td>Femoral Heads PBT-polyester</td>
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<td>1297</td>
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<td>308</td>
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<td>Tumor HI polystyrene</td>
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</tbody>
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²Boedeker Plastics, Shiner, TX.
³Computerized Imaging Reference Systems, Inc. Norfolk, VA.

**Table I. Materials, densities, and CT numbers for materials used in the construction of the pelvis and thorax phantoms compared to average patient CT numbers.**
polyester, lungs constructed of computerized imaging reference systems (CIRS) lung (inhale) phantom, and a polystyrene lung tumor. The shell has an angled anterior surface that simulates the slope of the chest. The thorax phantom has a removable imaging/dosimetry insert within the left lung. The materials selected for each component were of similar density and CT number to actual tissues, as shown in Table I. The insert was aligned within the phantom shell using an alignment notch. The phantom was built to simulate actual patient anatomy, as shown in the CT images in Fig. 7. The superior side of the phantom provides access to the insert containing anatomical structures as well as TLD and film dosimeters (Fig. 6). Two acrylic rods, each containing a TLD capsule at the tip, are inserted into hollow acrylic tubes that extend through the center of the heart and spine to provide point-dose measurements within these critical structures. A large acrylic tube accepts the imaging/dosimetry insert. This insert locks into an alignment notch located at the end of the tube in a unique orientation to ensure positioning reproducibility.

Similar to the pelvic phantom, the dosimetry insert for the thorax phantom is split in half along the axial plane corresponding to the center of the target to allow access to the film and TLD locations. The target is embedded in the lung substitute material so that a single insert serves as both the imaging insert and the dosimetry insert. The two halves slide along two threaded nylon guide rods that maintain the proper alignment of the superior and inferior film planes and the TLDs. The dosimetry insert accommodates TLD capsules in the superior and inferior halves of the target and radiochromic film in the axial, sagittal, and coronal planes. Each insert contains registration guide holes that are drilled through the outer acrylic sleeve and lung material to provide registration pinholes in the axial, sagittal, and coronal films.

B. Dosimeters

The dosimetry-system design and the selection of dosimeters for use within the phantom were based on compatibility with the TLD and radiochromic film dosimetry systems currently used at the RPC. These two dosimeters have been shown to be suitable for use within the phantoms owing to their well-characterized dose response, quantifiable fading, and a spatial resolution of ±2 mm in high-dose-gradient regions. Radiochromic film is approximately tissue equivalent and insensitive to light, and it has no significant angular dependence. A detailed description of the dosimeters used in the RPC QA phantoms and how they are analyzed has been provided by Molineu et al. The TLDs are used as the absolute dosimeter within the phantoms and are typically located near the center of the target and in the OARs. The film dosimeters are used as relative dosimeters that are normalized at a point to the corresponding TLD dose.

![Fig. 4. Coronal (left) and sagittal (right) reconstruction of phantom (top) and patient (bottom) anatomy.](image-url)

![Fig. 5. Pelvis phantom dosimetry insert is a solid cylinder of high-impact polystyrene that holds two pieces of intersecting radiochromic film in sagital and coronal planes. Two TLD capsules are located near the target center.](image-url)

![Fig. 6. Thorax phantom shown in supine position with superior end exposed. For clarity, lung insert is shown partially removed (see label). Inset shows lung insert disassembled with superior lung section removed showing insert cross section with tumor and film slits.](image-url)
C. Phantom commissioning

Once the phantoms were built, the construction of each phantom shell and the inserts was verified to confirm the machine-shop measurements, the CT values of materials, and the target and critical structure geometries with respect to one another and to identify any gross measurement errors made in construction and machining. Three millimeter axial CT scans of each phantom were acquired with both the imaging and dosimetry inserts using a GE Advantage CT scanner. Anterior-posterior and lateral scout views of the phantom shells were acquired with both inserts in place and with the phantoms empty (to improve contrast) and filled with water. The CT scans were imported into the ADAC Pinnacle TPS where measurements of the phantom shell width and height, insert diameter, CT densities, and sizes of all critical structures, positions of dosimeters, and structure and location of the dosimeter, with respect to the target center, were compared with the phantom drawings.

D. IMRT and 3D benchmark treatment plans

A benchmark prostate treatment plan was generated for the pelvis phantom using the NOMOS Corvus TPS. The dose prescription was 75.6 Gy to the 85% isodose line encompassing 98% of the target. The plan consisted of IMRT delivered through ten fields shaped with a dynamic multileaf collimator. The dose limits to the rectum, bladder, and femoral heads were 25, 38, and 45 Gy, respectively. The phantom was placed on the treatment couch and aligned with the lasers and phantom fiducials placed during simulation. The phantom was loaded into the phantom, and the phantom was reposited with the phantom to the prescribed treatment, the prescribed dose was reduced to 20 Gy in one fraction to accommodate the sensitivity of the dosimeters. The phantom was irradiated three times to irradiate three sets of dosimeters.

E. Comparison with TPS

Following the irradiation of each phantom, the TLD and films were removed and stored for an appropriate length of time before being analyzed. The measured results from the pelvis and thorax phantoms were compared with the dose distributions computed with the Corvus TPS and the Pinnacle TPS, respectively. Absolute doses were compared at each of the TLD capsule locations by taking the ratio of measured and TPS-calculated doses. The measured dose profiles scaled to the TLD doses through the region containing the targets in each phantom were compared with TPS profiles taken from the calculated treatment plans. Radiation-field localization agreement was determined by calculating the difference between the TPS and measured profiles in a steep gradient dose fall-off region.

F. Estimation of phantom reproducibility and systematic errors

The reproducibility of each phantom and each dosimetry system was determined by using the treatment technique for which each phantom was designed, i.e., IMRT for the pelvis phantom and 3D-CRT for the thorax phantom. The measure of reproducibility included the ability to reproduce the patient position, the uncertainty of the relative dose measured with radiochromic film, and the uncertainty of the absolute dose measured with TLD. The measured mean absolute dose and mean main axis profiles for the pelvis IMRT and 3D-CRT thorax treatments delivered precisely and according to the treatment plan were compared with RTOG-exported dose distributions from the CORVUS TPS and Pinnacle TPS, respectively.

III. ANALYSIS OF REPRODUCIBILITY OF RPC QA PHANTOMS

A. Verification of phantom geometry

Physical measurements were made of the phantom shell width, height, insert diameter, size of organs at risk, and...
locations with respect to the target center for the two phantoms. Because of the resolution of the CT scanner, submillimeter differences between the dimensions recorded on the mechanical drawings and the values measured during commissioning could not be determined. However, no gross errors were found for either phantom. The materials used to simulate the various organ structures within each phantom had CT numbers that were similar to actual patient CT numbers as shown in Table I. The comparison shows that the phantom and patient CT values agree to within ±8%.

B. Dosimeter registration with phantom coordinates

To properly characterize the dose distributions delivered to the phantoms, the film dosimeters must be registered in phantom coordinates. Each phantom contains interlocking pieces of radiochromic film and several TLD capsules. The coincidence between the target center and the intersection point of the radiochromic films was confirmed within the CT scan resolution, and no errors were found. Once inserted in the phantom dosimetry insert, films were marked with registration pinholes. The distances between the pinholes and the center of the target were determined. Multiple measurements demonstrated the reproducibility of the distance to be within 0.04 cm. The locations of the two TLD capsules in the target were verified by CT scans and by machinist measurements to be at 3 mm anterior-superior-left and inferior-posterior-right of target center, respectively.

C. Pelvic phantom measurement reproducibility

To determine the reproducibility of the measurement systems under conditions of intended use, IMRT treatments were delivered to the phantom. A single IMRT treatment plan was delivered to the phantom three times. Data were acquired, including absolute dose measurements at the target center and at each femoral head, and radiation field localization was measured by profiles through the target center. The reproducibility of the absolute dose measurements for the IMRT delivery technique was within 3% (1 standard deviation) for the target and OARs. The radiation field localization reproducibility, as demonstrated by the dose profiles (Fig. 8), was within 1.8 mm (Table II).

D. Thorax phantom measurement reproducibility

A single 3D-CRT treatment plan was delivered to the thorax phantom three times in order to ascertain the reproducibility of this QA system. The TLD dose measured in the target within the lung had a reproducibility of less than 0.5% (one standard deviation) for the three irradiations (Table II). The representative profiles for the three irradiations, as shown in Fig. 9, illustrate the good agreement of the data when the phantom is irradiated in a controlled manner. The difference between the profiles in the high-dose-gradient region at a level of 67% dose was ±2.4 mm (Table II).

IV. CONCLUSIONS

The high degree of reproducibility demonstrated using the pelvic IMRT and thorax SBRT phantoms indicates the usefulness of these phantoms in credentialing institutions to participate in specific NCI clinical trial protocols that utilize advanced technologies. In addition to credentialing, the

<table>
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<tr>
<th>Table II. Reproducibility of measurements for a DMLC delivery of an IMRT treatment to the pelvis phantom and a 3D-CRT treatment to the thorax phantom. The values shown are the standard deviation as a percent of the mean measured dose for absolute dose and millimeters for the profiles three irradiations of each phantom type.</th>
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<tr>
<td>Absolute Dose</td>
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Fig. 8. Representative pelvis phantom profile through target center on coronal plane. The negative axis is inferior to the target center. Film data are represented by solid lines and TPS data by circles.

Fig. 9. Representative thorax phantom profile through the target center in the axial plane. Film data are represented by solid lines and TPS data by circles.
phantoms are useful in assessing the heterogeneity calculation algorithms of various TPSs to assess whether reported doses corrected for heterogeneities are consistent between systems.

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