Design of an Anthropomorphic Intensity Modulated Radiation Therapy Quality Assurance Phantom

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Abstract - **The Radiation Physics Center (RPC), as part of its commitment to the Advanced Technology Consortium, is developing an anthropomorphic quality assurance phantom for the purpose of reviewing IMRT treatment modalities at institutions participating in NCI cooperative clinical trials. This study investigates the use of an inhomogeneous anthropomorphic phantom for dose verification of IMRT delivery modalities (compensators, dynamic MLC and serial tomotherapy) used in conformal therapy of the prostate. Because the phantom must be mailable, it is lightweight and water-fillable. It is heterogeneous with two interchangeable inserts. The first insert, used to acquire CT data, contains an imageable target and imageable critical structures with densities similar to human tissue densities. This insert provides relatistic geometries for dose constraints used in treatment planning. The second insert, used to acquire dosimetry data, contains precisely placed TLD and radiochromic film. This insert will measure target dose homogeneity to within 5% of the treatment plan calculated doses. It will measure field localization for high gradient regions to within 2mm of the treatment plan. The phantom will be tested for reproducibility and for ease of use at remote locations. Treatments will be planned on the phantom CT data set. Treatment plans for different IMRT treatment techniques will be comparable in both clinical requirements and dose constraints. With a focus on "common" clinical errors, tests will be devised to investigate the capability of this QA system to identify the magnitudes and origins of certain dose and field localization errors.**

I. Introduction

Intensity modulation, achieved by varying the fluence of the beam by changing each pencil beam weight across the field, provides a homogeneous dose distribution to the target volume while minimizing dose to the surrounding normal tissues. Intensity modulated radiation therapy (IMRT) generated dose distributions often have complex shapes with high dose gradient regions surrounding critical patient structures, limiting the usefulness of point detectors to regions within low dose-gradients for treatment verification. This offers unique challenges relating to both accurate and reproducible dose delivery and accurate and reproducible treatment verification. As a result, there is a no standardized system of quality assurance (QA) for the delivery of IMRT treatments. As part of its commitment to the Advanced Technology Consortium, the Radiation Physics Center (RPC) is developing an anthropomorphic quality assurance phantom for the purpose of reviewing IMRT treatment modalities at institutions participating in NCI cooperative clinical trials. This study investigates the design of an inhomogeneous anthropomorphic phantom for dose verification of IMRT delivery modalities (compensators, dynamic MLC and serial tomotherapy) used in conformal therapy of the prostate.

The purpose of the phantom is verify the ability of institutions to meet the criteria for field localization and three-dimensional dose delivery for a particular IMRT protocol. This should be accounted for in the phantom design. Specifically, the design of the phantom will allow the measurement of target dose homogeneity to within 5% and field localization for high gradient regions to within 2mm of the treatment plan. The phantom should comply with the established RPC mail-out remote auditing program. This means that the phantom must be lightweight and utilize currently available RPC data analysis systems with as little modification as possible. The phantom must be easy to image and treat in most IMRT systems. For imaging purposes, critical structures should be of slightly different density than the target. For treatment planning purposes, the critical structure and target shapes should provide the institution and the inverse planning algorithm with a realistic treatment challenge. The selection and commissioning of convenient dosimeters to be used within the phantom is necessary.

II. Materials and Methods

Dosimeters - Dose Response and Fading

Dosimeters used within the phantom must have a well characterized dose response and quantifiable fading as well as the ability to resolve to within 2 mm for high dose-gradient regions. The RPC has used encapsulated TLD powder for monitoring photon and electron beams since 1977 and 1982 respectively[5]. It has used radiochromic film in the remote monitoring of stereotactic radiosurgery for several years. For these reasons, TLD powder and radiochromic film have been chosen for use within the IMRT pelvic phantom. Each batch of TLD powder used in RPC capsules is evaluated by the RPC for uniformity, dose response and fading. It has been shown that the accuracy of the TLD readout system is as good as ion chambers for absolute dose measurements, and the system is precise to 1% [5]. Because radiochromic film has high spatial resolution and low spectral sensitivity, [3] it is well suited to detect IMRT produced high dose-gradient radiation fields. The infrastucture for film analysis will require a small

modification to the system currently used in analysing data from the stereotactic head phantom at the RPC.

The AAPM Radiation Therapy Committee Task Group 55 has put forth recommendations for the handling and evaluation of radiochromic film for use in dosimetry[1]. These recommendations were condsidered in the calibration of the film dose response. Two sheets of 12.7cm x 12.7 cm GafChromic (Nulcear Associates, Carle Place, NY) MD-55-2, lot 37350 film were cut into squares of approximately 3 cm x 3 cm. To note the direction parallel to the film coating application, one corner of each piece of the film was notched. For each dose from 3, 10, 20, …, 100 Gy three pieces of film were independently irradiated centered in the 10 cm x10 cm field at a depth of 1.5 cm in polystyrene with 10 cm of phantom backscatter material. A Varian Clinac 2100 C/D machine was set to 6MV,with a dose rate of 400MU/min. The SSD was set to 100 cm. The beam output was verified to be within 1.3% of calibration (1.000 cGy/ MU to water). Forty-eight hours after exposure, films were scanned by the Molecular Dynamics Personal Densitometer. It has a He-Ne laser light source with the peak centered at 633 nm, which is within the recommended range of absorbance peaks for RCF of 610 – 675 nm[3]. To obtain fading data, optical densities were measured on the same films 2 days and 4 days post irradiation and intermittently thereafter. Optical densities were determined by integrating over an area of approximately 2.5 cm^2 for each film square. Areas were carefully chosen to avoid undue noise interference (pin pricks, creases, lint particles). Three unexposed film squares were used to measure the background.

Phantom Design

Patient data and anatomical charts were surveyed for densities, and for geometry of normal tissue and critical structures.

III. Results and Discussion

Dosimeters - Dose Response and Fading

Net optical densities were obtained by subtracting the background from the film. The data were plotted and a linear fit was forced through zero. The dose response curve from 0 to 60 Gy is shown in figure I. Since dose rate affects above 60 Gy can be as high as 10 %[2] and common IMRT boost treatment prescriptions in our clinic are between 30 and 50 Gy, we can fit the dose response data from 0 – 60 Gy without limiting the dosimetric potential of the phantom. The dose response relationship is OD_{NET}=0.0175 * Dose, where OD_{NET} is the net optical density of the film. For radiochromic film, fading over time results in an increase in absorbance. This can be seen in figure II. The dose factors (slope of linear fit) for three arbitrary days post irradiation are shown in table I. Q is the dose factor for a particular day divided by the dose factor for day two. This table shows an increase in dose factor by 4% over a period of 3 weeks post irradiation. There is less than 2% difference between 19 and 8 days post irradiation and there is less than 1% difference between 13 and 19 days. These results show excellent agreement with the published increase in OD of 4% for up to two weeks beyond the irradiation date[2].

FIGURE I

Linear dose response of radiochromic film with maximum irradiation dose

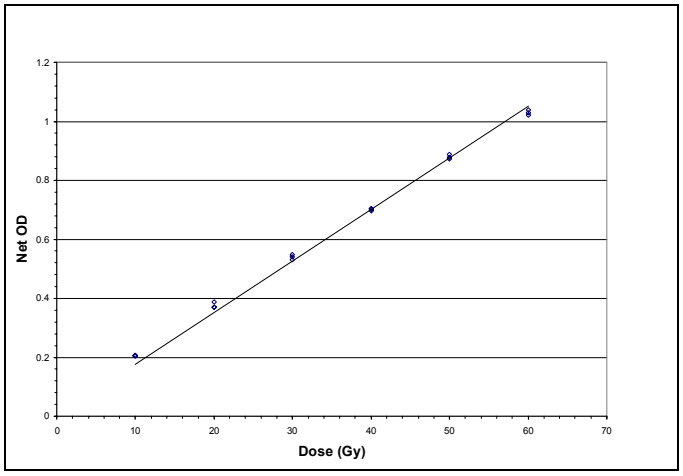
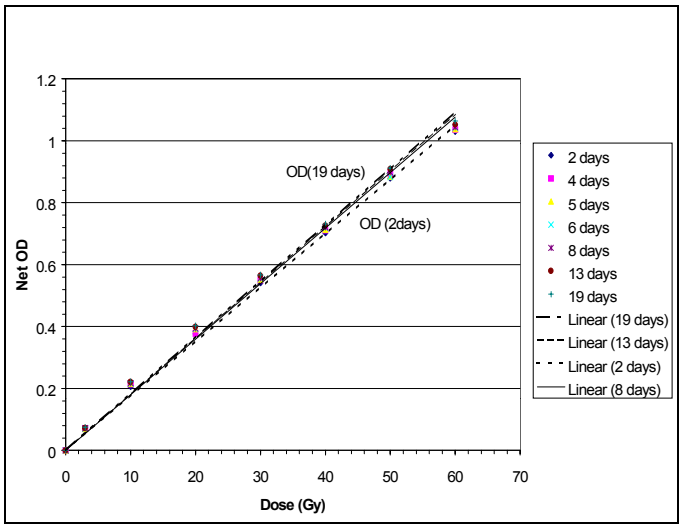


FIGURE II

Linear dose response of radiochromic film over time



A comparison between net optical densities of films irradiated to the same dose but scanned at perpendicular directions in the scanning bed showed that differences of 8 to 18% is possible. This emphasizes the importance of noting the direction of the film coating application and orientation of the film in the scanner. Observations of scanned film images show interference fringes as a result of the monochromatic light source. Tests are underway to smooth out the fringes.

TABLE I

Dose Factors for arbitrary days post irradiation. Q is the ratio of the dose factor for a particular day to the dose factor on day 2.

Day Post irradiation	Dose Factor	Q
2	0.0175	1.000
13	0.0181	1.034

19	0.0182	1.040

Phantom Design

Remote dose monitoring requires that the phantom be mailable and therefore light-weight. Thus, we have designed the phantom to be a hollow shell that is water fillable. It is heterogeneous with two interchangeable inserts. The first insert, used to acquire CT data, contains an imageable target and imageable critical structures with densities similar to human tissue densities. This insert provides relatistic geometries for dose constraints used in treatment planning. The imaging insert is also water fillable. The second insert, used to acquire dosimetry data, contains precisely placed TLD and radiochromic film. This insert will measure target dose homogeneity to within 5% of the treatment plan calculated doses. It will measure field localization for high gradient regions to within 2mm of the treatment plan. The estimated weight of the phantom and its inserts is about 15 to 20 pounds.

The data in table II reflect the physical densities of the chosen phantom materials as well as the mean densities from a survey of three patient GTV densities. Rectum density values are highly variable depending on filling. The phantom rectum will have a polyethylene wall. The rectum of the phantom will be filled with wax, which will then be pierced with a wire to generate an air cavity. While CT values for each of the target and critical structures have been obtained from patient data, we are awaiting arrival of the phantom materials in order to do a comparison of CT numbers.

TABLE II

A comparison of phantom material densities[5] and tissue densities.

Region of Interest	Imaging Insert	Material density (g/cm^3)	Patient density (g/cm^3)
Insert (Shell only)	acrylic	1.17	-----
Rectum	Polyethylene & wax	0.95 & 1.00	0.63
Prostate	Nylon	1.15	1.14
Bladder	polyethylene	0.95	0.87
Femoral Heads	PVC	1.37	0.93
Marrow	acrylic	1.17	-----
Phantom Shell	PVC	1.37	-----

The phantom geometries shown in figures 4 and 5 are derived from patient data and physician consultation. The marrow of the right femoral head is centered within the femoral head, while in the left (patient left) femoral head, it is offset. This is to introduce asymmetry into the phantom. It serves the purpose of allowing the treatment planner to identify phantom left from phantom right. And it will serve the purpose of unmasking errors in the inverse planning and optimization algorithm that can be hidden by symmetry. The imaging insert is large enough to accommodate all the critical structures and it is water fillable. The dosimetry insert is the same size as the imaging insert, but it is made of high impact polystyrene. It contains two TLD capsules on either side of two perpendicularly intersecting radichromic films 12.7 cm x 12.7 cm in size. Film data will be normalized to the TLD readings. The films are placed in coronal and sagittal planes, which is optimal positioning for determining the dose profiles in the directions of the dose limited structures (femoral heads, bladder and rectum). Figure 6 shows the film and TLD coverage of the targets and critical structures. The dosimetry insert is high impact polystyrene (1.044 g/cm^3)[4]. Both inserts will include alignment notches to ensure accurate placement of the inserts within the phantom. The Femoral heads are non-removable and will provide heterogeneity during irradiation. TLD capsules may be inserted into the femoral heads to obtain additional dose information.

FIGURE III

A transverse slice of the anthropomorphic phantom through the middle of the prostate is shown above. The top of the page is anterior, right of the page is phantom left, bottom of the page is posterior and the left of the page is phantom right.

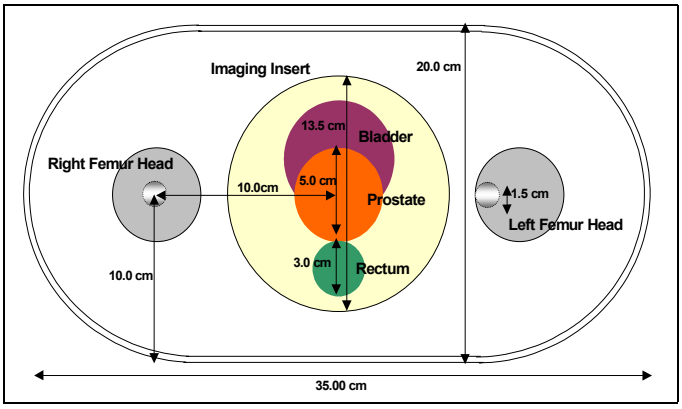
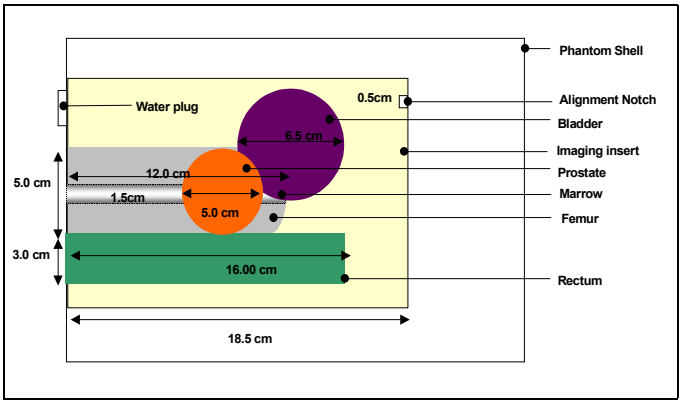


FIGURE IV

Anthropomorphic mailable phantom. This is a saggittal slice through the middle of the prostate. The top of the page is anterior and the right of the page is superior.



IV. CONCLUSIONS

A heterogeneous, anthropormoric, mailable dose-verification phantom has been designed as a comprehensive quality assurance tool for IMRT. It

provides realistic heterogeneities and dose constraining geometries for use in treatment planning. The dosimetry insert can provide IMRT treatment absolute dose, target homogeneity and localization information. The dosimeters used in the phantom have well characterized dose responses. Radiochromic film has a linear dose response with reasonable and quantifiable fading.

The phantom will be tested for reproducibility and for ease of use at remote locations. Treatments will be planned on the phantom CT data set. Treatment plans for different IMRT treatment techniques will be comparable in both clinical requirements and dose constraints. With a focus on "common" clinical errors, tests will be devised to investigate the capability of this QA system to identify the magnitudes and origins of certain dose and field localization errors.

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Figure V

Transverse slice of the anthropomorphic phantom with the dosimety insert. The target and critical structures are projected behind the film and TLD to demonstrate target and critical tissue coverage by the dosimeters.

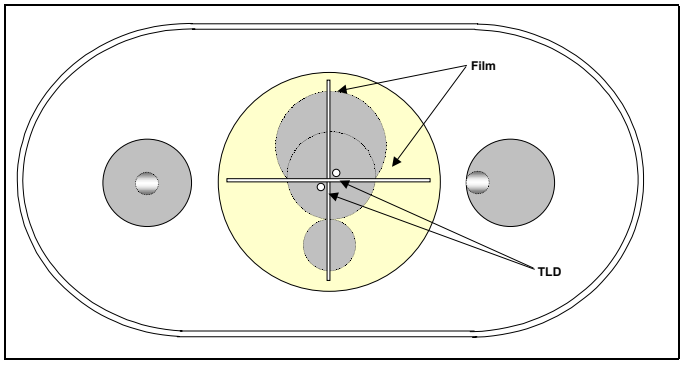

Figure VI.