Original Article

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Design and Implementation of a Multipurpose Phantom for Advanced Radiotherapy Treatment Delivery Verification

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ABSTRACT

Introduction: Radiotherapy alone or in conjunction with surgery or chemotherapy is one of the principal modality for the treatment of cancer by using ionizing radiation. Achievement of higher tumor control probability with reduced treatment morbidity is the ultimate goal of radiotherapy and in order to successfully achieve this, intensive dosimetry is necessary during the implementation of the technique and treatment verification processes.

Methodology: Computed tomography (CT) images were obtained as per normal departmental protocols. The external outline, target volume, femoral heads, bladder, and rectum were delineated using the Eclipse planning system. Each organ and bone structure for each individual slice was milled using a Pinnacle milling machine. Moulds were created using external contour for the organs; liquid material was poured into the moulds and allowed to cure, forming solid organs in close contact to remaining structures. A Scanditronix Wellhofer CC01 chamber was chosen for absolute dose measurement protocols. A water fillable applicator holder was made to use the intra-cavitary brachytherapy applicators. The phantom slices were determined along transverse planes. To facilitate a high level of reproducibility, the phantom design incorporated two positioning rods passing through each slice.

Results: The phantom was simple to assemble and reproducible with no discernible displacement. The CT numbers of the phantom materials and those of the delineated regions on the CT of the patient used to model the phantom were sampled using the Eclipse planning system and indicates agreement. The doses measured with the ionization chamber and Thermoluminescent Dosineter **(**TLDs**)** were compared with Treatment Planning Systems (TPS) calculated dose in different locations in the phantom like target volume, bladder, rectum, left, and right femoral head. The average measured dose agreed with the TPS calculated dose for both teletherapy and brachytherapy treatment plans.

Conclusion: A phantom based on realistic anatomy and heterogeneity can be used to comprehensively assess the influence of multiple aspects of the radiotherapy treatment process and dose delivery.

INTRODUCTION

Radiation therapy refers to the treatment of disease by means of radiation. It is generally used for the treatment of malignancy or cancer. The basic modalities of cancer treatment are surgery, radiotherapy, and chemotherapy. Now a days radiotherapy alone or in conjunction with surgery or chemotherapy is one of the principal modality for the treatment of cancer by using ionizing radiation. The inception of radiotherapy goes back to the discovery of X-rays and continuously developed with new skills and approaches.

The aim of radiotherapy is to deliver as high and homogenous dose as possible to diseased tissue without causing unnecessary side effects. This aim recognizes that it is not enough to destroy tumor cells and prolong the life of a patient, but the life must be of high quality. Achievement of higher tumor control probability with reduced treatment morbidity is the ultimate goal of radiotherapy and in order to successfully achieve this, intensive dosimetry is necessary during the implementation of the technique and treatment verification processes.

Efficient dosimetry is possible when a well-designed phantom is available. The required characteristics of a phantom can be summarized as follows: It needs to facilitate dosimetry not only in homogeneous tissue-equivalent media, but also in heterogeneous environments. This is particularly important for advanced treatment technique commissioning, since disequilibrium at the boundary of different tissues is known to be more pronounced in small radiation fields and hence the accuracy of doses computed by radiotherapy treatment planning systems needs to be verified. The design needs to allow for dose measurements with diverse types of radiation detectors, because choosing a suitable detector in advanced techniques can be a challenging and even confounding task. In addition, the positions of the heterogeneous structures and the detectors in the phantom need to be geometrically adjustable to accommodate an analysis of dose and dose distributions under various conditions.[1-4]

However, none of the commercially available phantoms simultaneously satisfy these requirements. Rather, commercial phantoms entail restrictions in measuring the doses and the dose distributions that are specific to individual patient treatment conditions.[5]

The main design criteria followed in this study were suitability for evaluation of radiotherapy treatments, representative of a median-sized patient in the treatment position, anatomically accurate in terms of geometry, nontoxic materials which will maintain structural integrity, physical and electronic densities to be approximately radiologically equivalent to real tissue, organs to be visually distinguishable for treatment planning, able to accommodate a variety of dosimeters in clinically relevant locations, able to be rapidly assembled and disassembled, demonstrate reproducible assembly and overall weight suitable for manual handling.[6] We treat large number of patients of carcinoma cervix and the treatment is delivered by both external beam radiotherapy and brachytherapy. Hence, this study was aimed to design and fabricate an anthropomorphic female pelvis phantom in which heterogeneities were incorporated to achieve realistic dosimetric conditions. The provisions to incorporate different dosimeters as well as different brachytherapy applicators were made.

METHODS

Patient tissues were allocated to three distinct groups: bone, organ, and tissue. As the exact chemical composition for the materials was protected by industrial confidentiality, material testing was limited to relative testing against water using CT.[7] This allowed for determination of their attenuation using the corresponding Hounsfield unit (HU) and the linear attenuation coefficient for water measured at the corresponding photon energy.[8] CT scanning was replicated as per the protocols used for the patient images. The electron density of the materials chosen for fabrication was based on HU to electron density calibrations. The electron densities agree with data published by Cassell, which utilizes the generalized Batho calculations.[9]

Computed tomography (CT) images were obtained as per normal departmental protocols on a (Philips MX-16) scanner. The external outline, target volume, femoral heads, bladder, and rectum were delineated by a radiation oncologist using the Eclipse planning system (Varian Medical Systems, USA). Delineated structures and external contour were altered or smoothed in shapes as required for milling.[10,11]

The phantom design data for the organs, bone and external contour was separated according to each transverse phantom slice. Each organ and bone structure for each individual slice was milled using a Pinnacle milling machine (EXCEL machine tools, England).

Moulds were created using external contour for the organs and were accurately positioned. Liquid material was poured into the moulds and allowed to cure, forming solid organs allowing close contact to remaining structures. After the organs had solidified, recesses were drilled and labelled to meet the design specification for the TLD measurement points. 3D imaging facilitated definition of the desired positions for TLDs, radio chromic films, chemical dosimeters, OSLDs and ionization-chamber detectors. The TLD positions were located at points of clinical interest, these being known disease recurrence sites, within critical organs or near structure junctions. Positions in the bladder and rectum allow assessment of dose within these normal structures. Where spatially allowable, multiple TLD points were allocated at each measurement point to improve measurement statistics as shown in table 1.[12-14]

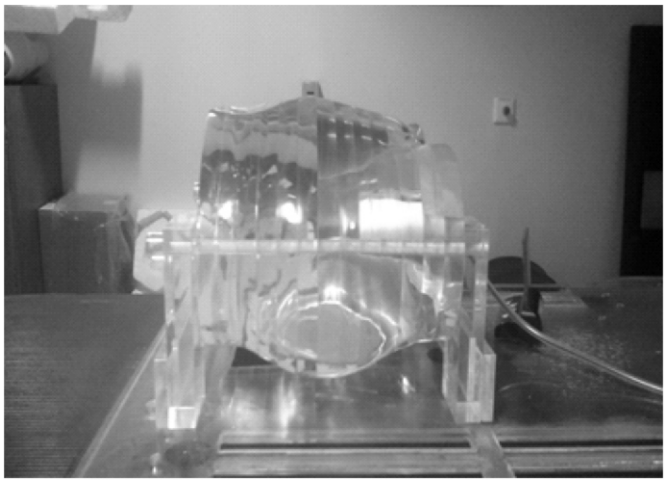
A ScanditronixWellhofer CC01 chamber was chosen for use in the phantom due to its small size, tissue equivalence, robustness, and known correction factors for

absolute dose measurement protocols. The external contour of the ion chamber was outlined to be incorporated into the design. The outline was integrated onto the slices to allow for exact positioning. The chamber was embedded at the center of the cervix volume with minimal air gap surrounding the measurement tip. A dummy chamber was also milled separately in phantom material for use in the chamber cavity when the phantom was to be CT scanned.

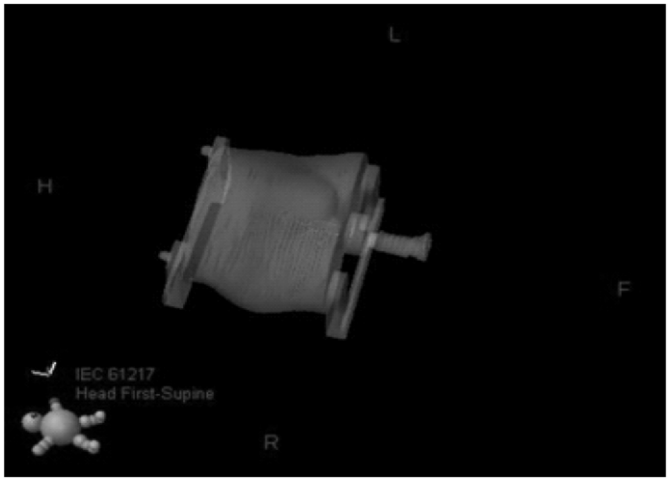
A water fillable applicator holder was made to use the intra-cavitary brachytherapy applicators. A slab phantom design deemed appropriate to minimize air gaps between the slices and allow for rapid assembly and disassembly. The phantom slices were determined along transverse planes. To facilitate a high level of reproducibility, the phantom design incorporated two positioning rods passing through each slice. The fabricated phantom is shown in figure 1.

Table 1: Locations of TLD measurement points in the phantom

Anatomical location of the measurement points	Number of measurement points
Target Volume	2
Bladder	4
Rectum	4
Left Femoral Head	3
Right Femoral Head	3
Left Regional Lymph Node	1
Right Regional Lymph Node	1



(a)



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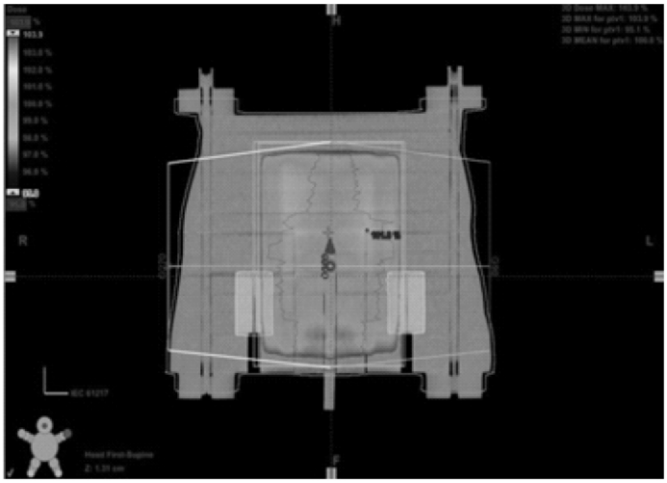
(c)



(d)

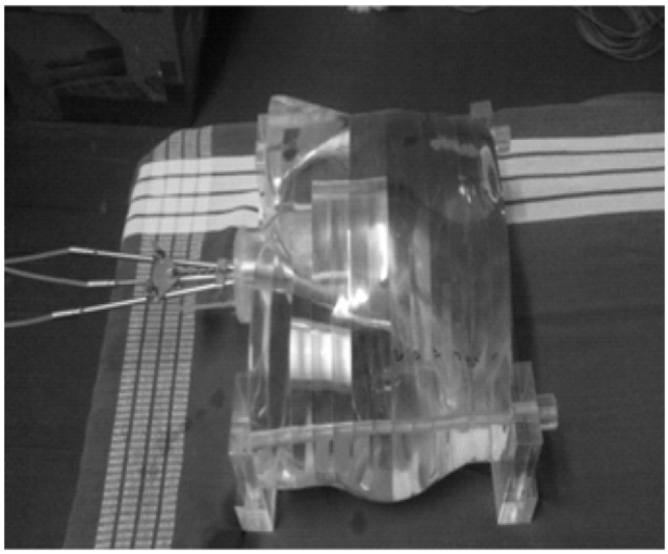
Figure 1: (a, b) Assembled phantom, (c) setup, (d) treatment plan for External Beam Radiation Therapy (EBRT).

RESULTS

The phantom was simple to assemble and reassemble with positioning rods and the phantom slices could be repositioned with no discernable displacement. The dimensions and relative location of anatomy matched the design. The fully assembled phantom weighed 15 kg. The CT numbers of the phantom materials and those of the delineated regions on the CT of the patient used to model the phantom were sampled using the Eclipse planning system. The values indicate the agreement between the phantom and patient CT numbers within the tolerances of the sampling (Figure 2).

The dose measured with ionization chamber was compared with TPS calculated dose in different locations like target volume, bladder, rectum, left femoral head and right femoral head. The average measured dose agreed with the TPS calculated dose. The percentage deviations were within 1% for all structures and maximum percentage deviation found was 0.79% for the rectum.

The measured point doses are the average of the four TLD disks placed at each measurement point. The percentage deviation was within 3% for all measurement points and maximum value of percentage deviation was 2.79% for rectum. The agreement between the measured dose and the TPS calculated dose indicates the treatment delivery accuracy.



(a)

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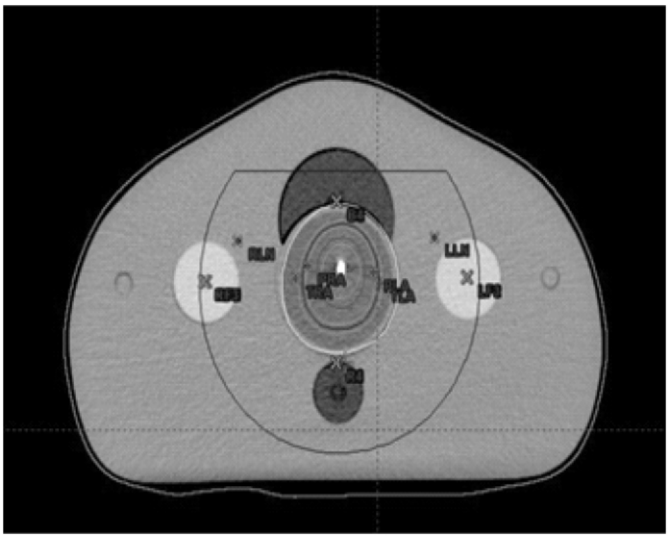
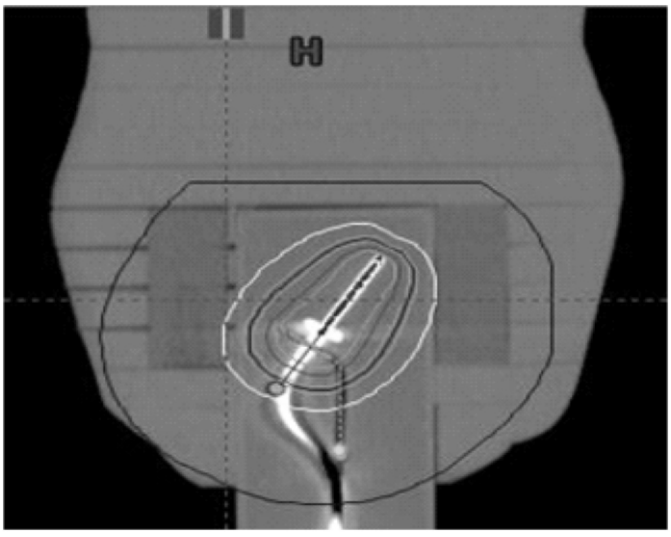


(c)



(d)

Figure 2: (a) Phantom setup, (b) applicator holder and (c), (d) treatment plan for Intra-Cavitary Brachytherapy (ICBT).

The phantom with the HDR ICBT applicator insert was CT scanned and a brachytherapy plan was generated using Brachyvision planning system. The plan was executed on a Gammamedplus HDR machine and the variation between planned and measured doses at clinically important points were evaluated using TLD roads. The percentage deviation for all measurement points was within 3% and maximum value of percentage deviation observed was 2.38% for the right femoral head position.

DISCUSSION

To assess approximate CT number matching, the phantom was positioned in the CT scanner (Philips MX-16) and helical scans taken (120 kVp; 230 mA; 512x512 pixels; 2mm slice intervals) and the images were imported into the Eclips planning system (Varian Medical Systems, USA). The CT numbers were sampled, using the CT number /HU software tool within the planning system, for the phantom materials and those of the delineated regions on the CT of the patient used to model the phantom. The median CT values were compared and tolerances were defined according to maximum and minimum values of the sampling. The results were found similar to the results from literature.[3,5,6,8]

Lithium-fluoride doped with magnesium and titanium (LiF:Mg,Ti) TLD-100 square rods of dimensions 1×1×6 mm^3, with a detector volume of 6×10^{-3} cc was used for measurements. The effective atomic number Z_{eff} was 8.2. Due to large dose gradients involved, TLD chips were not preferred. Before each experiment, TLDs were annealed according to technique proposed by Booth et al[15]and Weller et al.[16] This process consists of heating the TLD rods in an aluminium tray at 400ºC for one hour before irradiation and then10-15 minutes of heating at 100C before readout. Using the glow curves, Dhar et al[17] showed that pre-irradiation annealing and pre readout annealing gave the same results. Hence, pre-readout annealing method was adopted. The response of the TLD rods was measured using an automated Harshaw TLD reader (model 2000). The area under the glow curve for a temperature of 270ºC was evaluated to obtain TL output in nC. For an ideal batch of TLDs, all would give the same response when exposed to the same amount of radiation. However, differences in their physical properties (mass, size etc.) make the response different from one another; therefore the response of individual rods was compared with the average response of the entire batch. These relative responses, termed Elemental Correction Factors (ECF) were determined by irradiating the whole batch of TLD rods to a dose of 2Gy within a broad beam 20 cm × 20 cm at a depth of 5 cm with appropriate water equivalent build up thickness and 10 cm thickness solid water phantom slabs for backscatter and SSD 80 cm in Co-60 γ-rays from Theratron-780C telecobalt unit. The TLD rods were placed in a square matrix of holes machined in a 25 cm × 25 cm slab of polymethylmethacrylate (PMMA). To avoid any confusion, the array numbers of the TLD rods matrix were used as identification numbers of the rods. The ECF were determined five times and those showed more than ±3% variations were discarded. For all others, the ECF factors are the average of the five determinations. It has been observed throughout these experiments that the ECF factors were stable.

Response of the TLD rods per unit dose to water were studied by exposing each group of 5 TLD rods to doses ranging from 10cGy to 1000cGy, with an interval of 10cGy up to 100cGy and beyond with an interval of 100cGy upto 1000cGy in Co-60 γ-rays from Theratron-780C telecobalt unit and 6 MV photons from Varian Clinac 2100 DHX unit. The response of TLDs exposed to same dose was corrected by their corresponding ECF, and the average response was obtained. The TLDs response with increasing dose was linear upto 10Gy.

The phantom was tested by comparing planned and measured doses of 3D conformal plans for cervix cancer treatments. The methodology involved loading the phantom with the dummy chamber in the chamber cavity (to act as visual cues for identifying the point doses on the treatment plan). The phantom was positioned in the CT scanner (Philips MX16) and helical scans of 2mm slice intervals were taken. Four-field conformal treatment plans were generated using the Varian Eclipse 3D planning system (AAA algorithm, Varian Medical Systems, USA). One plan with per fraction dose prescriptions of 2Gy and another plan with per fraction dose prescription of 1.8Gy. The plan included contouring of tumor volumes, bladder, rectum and femoral heads. Ion chamber readings were recorded and interchange of TLDs took place between each of the fractions which were delivered with 6MV x-ray beams from a Varian Clinac DBX accelerator (Varian Medical Systems, USA).[18]

For the brachytherapy treatment, dose was calculated by using CT scan images produced in a simulation of patients who were subjected to a tandem and ovoid in intra-

cavitary brachytherapy for carcinoma cervix.[19] Point A was configured 2 cm away from both the anterior and lateral side of the cervical os.[20,21] Four reference points were configured to bladder and rectum to determine the rectal and bladder doses in a simulation treatment. Three measurement points each for left and right femoral heads also was determined to evaluate the normal structure doses. Regional lymph node positions on both left and right sides were also located.[22,23] A treatment planning system (Brachyvision) was used for dose calculation.

CONCLUSION

A phantom based on realistic anatomy and heterogeneity can be used to comprehensively assess the influence of multiple aspects of the radiotherapy treatment process and dose delivery. The physical dimensions of the phantom fabricated, the constituents and overall dimensions matched the design, the weight was suitable for manual handling, and the dosimeter locations were accurate and were robust on reassembly.

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