Technical Note

Radiation dose verification using real tissue phantom in modern radiotherapy techniques

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ABSTRACT

In vitro dosimetric verification prior to patient treatment has a key role in accurate and precision radiotherapy treatment delivery. Most of commercially available dosimetric phantoms have almost homogeneous density throughout their volume, while real interior of patient body has variable and varying densities inside. In this study an attempt has been made to verify the physical dosimetry in actual human body scenario by using goat head as "head phantom" and goat meat as "tissue phantom". The mean percentage variation between planned and measured doses was found to be 2.48 (standard deviation (SD): 0.74), 2.36 (SD: 0.77), 3.62 (SD: 1.05), and 3.31 (SD: 0.78) for three-dimensional conformal radiotherapy (3DCRT) (head phantom), intensity modulated radiotherapy (IMRT; head phantom), 3DCRT (tissue phantom), and IMRT (tissue phantom), respectively. Although percentage variations in case of head phantom were within tolerance limit (< ± 3%), but still it is higher than the results obtained by using commercially available phantoms. And the percentage variations in most of cases of tissue phantom were out of tolerance limit. On the basis of these preliminary results it is logical and rational to develop radiation dosimetry methods based on real human body and also to develop an artificial phantom which should truly represent the interior of human body.

Key words: Head phantom, millennium 80 multileaf collimator system, real tissue, tissue phantom

Introduction

External radiation therapy has seen improvement in its day-to-day dose delivery technique and continued ascendance for dose escalation in the target volume for enhanced outcome. Initially radiation dose was delivered mostly by simple square open field using mainly cobalt as a radiation source.[1,2] Recent innovations have given several options for radiation treatment. A basket of energies are available and selection of suitable beam energy depending on the depth of tumor has become a standard practice to deliver tumoricidal dose. High energy linear accelerator (LA) with on-board imaging (OBI) system and computer-controlled multileaf collimator (MLC) has brought paradigm changes in the practice of radiotherapy. It has become possible to deliver large escalated dose to target and without exceeding the normal organs tolerance. Using these available techniques highly conformal and homogeneous dose can be delivered to target volume with less than 1 mm reproducible position accuracy. Now days, LA with multiple energy X-rays and unfiltered beam with very high dose rate are available. Multiple energy LA has option for selecting low energy or high energy photon beam or combination of both for low or high depth tumors and better homogeneity.[2]

Dose in radiotherapy has connotation of cure. Success of planned dose on treatment planning system (TPS) and its outcome is entirely depended on the delivered dose to the respective site of patient with reproducible accuracy of planned dose or within tolerance. For this, many techniques are available to compare the delivered dose with planned dose. Generally absolute dosimetry is preferred in which point dose is measured at the specified and reference depth using ionization chamber and currently commercially

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available phantoms like slab phantom.[3,4] *In vivo* dosimetry using thermoluminescent dosimeters (TLD) or diodes is also in practice. In this method, TLD or diodes are placed on patient body at reference points and delivered dose is measured. Although in this technique dose is measured at skin and not in depth.[5] This technique could be utilized to measure doses in rectum and bladder in patients of pelvic tumors. For reference dosimetry film, quality assurance (QA) is done in which film is placed in slab phantom at a particular depth at which the dose distribution is to be compared, then planned dose is delivered on it and then resultant density of film can be correlated with dose at each point on film which can be compared with the planned dose distribution. The density correlation with dose and comparison is done by commercially available film QA dosimetry systems, for example, OmniPro-I'MRT.[6,7] Reference dosimetry is also done using electronic portal imaging device (EPID), where planned dose is delivered by LA and recorded by EPID and then it can be compared with the planned dose distribution.[8,9]

In all above mentioned methods, the medium used is having homogeneous density while actual patient body has heterogeneous medium. International Commission on Radiation Units and Measurements (ICRU) which is an international body to provide guideline for radiation dosimetry and delineation of volumes of interest as elaborated in its report number 50, 62, and 83 (ICRU, 1993; 1999; 2010) have illustrated the mechanism of accurate and clearly target volume delineated.[10-12] ICRU 83 published in 2010 propounds that single biggest cause of treatment failures are geographical miss due to inaccurate target delineation and dosimetric variation more than 3%.[12] To improve the dosimetric part there is a need of improving the dosimetric equipment and procedure of patient specific QA.

There are various methods to achieve accuracy in dosimetry and they are based on International Atomic Energy Agency (IAEA) recommendations published in technical reports series number 277 and 398.[13,14] It is clearly established today that human body comprises of fat, tissue, bones, and air cavities, and they influence the transport of photon and electron energy which results in consequential dose delivery to target volume. It is therefore essential to stabilize a quality dosimetric practices and pretreatment verification.

The medium of all reference QA phantoms which are in practice is homogeneous like water phantom, slab phantom, acrylic body phantom, etc., that is, medium is made of material with same density throughout its volume. Although the anthropomorphic phantom has heterogeneous medium but it is very basic phantom which cannot be considered similar to human body. The methods mentioned in AAPM Task Group Report 120 (intensity modulated radiotherapy (IMRT) dosimetry tools)[15] also prescribes the similar kind of QA procedures.

Materials and Methods

Mammals include most of the animals and human beings and the body tissue actually mimic each other. We used one of the mammals "GOAT" for our study. Goat head and goat meat (with bones and air cavities naturally existing in it) thrown as waste material by meat shops were used to construct two kinds of phantoms namely "head phantom" [Figure 1a] and "tissue phantom" [Figure 1b]. And for dose measurement 0.13 cc ionization chamber (IBA Dosimetry, Germany) and DOSE1 electrometer (IBA Dosimetry, Germany) was utilized.

Head phantom was goat head wrapped in polythene and tissue phantom was made by goat meat giving it cubic shape of dimension approximately 20 cm × 20 cm × 20 cm by putting it in thermoplastic sheet (Orfit) molded in required shape with having thin polythene pasted inside to hold the tissue in same physical state. Ion chamber was fixed in the cavity prepared by screw driver at approximately geometrical center of phantom volume and was kept at same position till the end of experiment. Three fiducial lead markers were put on two bilateral points and one anterior point on surface of phantom in same cross-sectional plan to make three reference points. Head phantom was utilized for first experiment and tissue phantom was utilized for second experiment. Both experiments were done on 2 different days using same methodology.

Siemens SOMATOM Definition AS scanner (Siemens Medical Systems, Germany) has been utilized for computed tomography (CT) of both the phantoms and CT images of 3 mm slice thickness were taken for planning purpose. Then phantom along with ion chamber and attached accessories was kept in freezer during the period of treatment planning to prevent decomposition and the tissue conditions remain same throughout the period of experiment.

The CT images were imported on TPS Eclipse version 8.9 (Varian Medical Systems, Palo Alto, CA) and various types of plans already done for actual patients were exported on phantom and dose was calculated using anisotropic

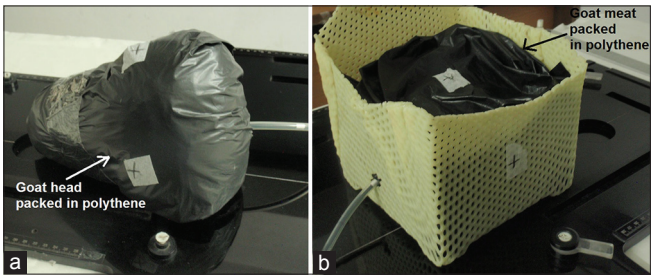

Figure 1: Photographs of the (a) head phantom and (b) tissue phantom

analytical algorithm (AAA) version 8.9.08 with grid size of 0.25 cc.

The patient plans selected for head phantom were those planned for brain and head-and-neck (H and N) tumors and the plans selected for tissue phantom were for lung, breast, and pelvic tumors. Field arrangement for IMRT plans was done in such a way that all fields were coplanar (CP) with couch angle 0° and no parallel opposed fields were placed, some plans for brain tumors had one none-CP (NCP) field with couch angle 90°/270° and gantry angle from 330°/30° to 350°/10°. Two fields at each gantry angle were also used in some plans which had large target volumes, as if field exceeds 14.5 cm in x-direction it gets split in two fields automatically. The splitting is because of the limitation that is present in MLC, where in the maximum distance between the most retracted and extended MLC, cannot be more than 14.5 cm. And in this way maximum of 18 fields at nine gantry angles were used in some plans.

Dose constraints and adequate weights were given for organs at risk (OAR) and target volumes (planning target volume (PTV), clinical target volume (CTV), and gross tumor volume (GTV)). Varian leaf motion calculator version 8.9.08 was utilized to calculate leaf motion for dynamic dose delivery. All IMRT plans were done with 6 MV photon beam and dose volume optimizer (DVO) was used for plan optimization. AAA was used to calculate doses with grid size of 0.25 cc.

Three-dimensional conformal radiotherapy (3DCRT) plans were generated by simple two to five fields in single plane with couch angle 0°, some plans for brain cases had NCP field with couch angle 90°/270° and gantry angle from 330°/30° to 350°/10°. Two plans with junction fields were also chosen for this study in which plans were made by 3DCRT technique for carcinoma of breast under which two tangential fields (couch 0°, gantry angles 310°/50°–325°/35° and 130°/230°–145°/215°) with collimator Y2 fully closed and one anterior field (couch angle 0°, gantry angle 0°) with collimator Y1 fully closed were used. The isocenter of plan was placed at junction of PTV for chest wall and PTV for supraclavicle region. All plans were generated without wedges.

All 3DCRT plans were done by using 6 MV, 15 MV, or combination of both photon energies. Doses were calculated by using AAA with 0.25 cc grid size. Weight of particular fields in some plans was decreased/increased by changing monitoring units (MU) wherever required to manage hot/cold spot and dose homogeneity.

Figure 2a and b shows the dose distribution on CT slices of head phantom and tissue phantom. After approving all the plans were exported to high energy medical LA Clinac DMX (Varian Medical Systems, Palo Alto, CA) having

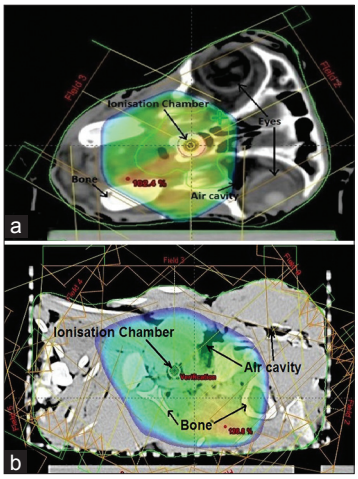

Figure 2: Dose distribution in case of (a) head phantom and (b) tissue phantom

photon energies of 6 and 15 MV and electron energies of 6, 9, 12, and 15 MeV. This LA is equipped with Millennium 80 MLC. Millennium 80 MLC system has 40 pairs of leaves and MLC leaf width projected at isocenter is 1 cm. The MLC leaf ends are rounded. The interleaf leakage is minimized by tongue and groove arrangement. In dynamic/moving window treatment mode, standard MLC leaf speed is 2.5 cm/s. The MLC workstation records the system status (MLC leaf positions) during MLC treatment delivery. TPS and 4-dimensional treatment console (4DTC) systems are networked through networking system ARIA.

The phantom was taken out of the freezer and was set on LA-couch with the help of reference points in same position as it was on CT-couch. To verify the position cone beam CT (CBCT) images were obtained using OBI system (Varian Medical Systems, Palo Alto, CA) with half bow-tie filter and compared with reference CT images. The minor shift in position was corrected.

After position verification all IMRT plans were delivered by LA with dynamic dose delivery technique and 3DCRT plans with planned open field technique along with accessories. Dose for each plan was measured using electrometer connected to the ion chamber which was fixed in phantom. These measured doses were compared with doses planned on TPS.

Results and Discussion

A study on patient specific absolute dosimetry using goat head and goat meat for improvement in dosimetry in modern radiotherapy techniques has been done to evaluate the outcome of real tissue based measurements. The mean % variation between planned doses and measured doses was noted as 2.48 (standard deviation (SD): 0.74), 2.36 (SD: 0.77), 3.62 (SD: 1.05), and 3.31 (SD: 0.78) for 3DCRT (head phantom), IMRT (head phantom),

3DCRT (tissue phantom), and IMRT (tissue phantom), respectively.

Although % variations in case of head phantom were within tolerance limit (< ± 3%) prescribed in ICRU 83, but still it is higher than the results obtained by using routine QA phantoms of homogeneous density. Percentage variations in case of tissue phantom were higher, although the higher variations in this case may have minor contribution of possibility of small change in volume during the period of around 3 h from CT scan to dose delivery. Measurements of this study indicate that most of variations are higher than recommended by international body of < ± 3% (ICRU 83).[12] Such variations may have large implication in treatment outcome in modern radiotherapy. While in case of routine patient specific absolute dosimetry using commercially available slab phantom the variation between measured and TPS calculated dose values is always found within ± 3%, and in most of the cases it comes within ± 1%, while rarely goes above ± 2%. It is as the medium in slab phantom is made of material with same density throughout its volume.

Phantoms used in this study had been made of goat head (head phantom) and goat meat (tissue phantom) which had inhomogeneous medium having bones, tissues, and air cavities same as in human body. Although pig tissue structure is more similar to human tissue structure but due to easy availability of goat meat in India, it has been selected for this study.[16] Although the interaction of therapeutic radiation with every type of tissue in human body is of same kind that is predominantly Compton scattering. The number of secondary electrons produced depends on density of medium and hence following points could be made out.

Soft tissue-bone interface

As density of soft tissue is lesser than bone so lesser number of secondary electrons is produced and when they enter in bone some of them reflect back. In this way reflected electrons deposit dose in soft tissue near interface area, while dose deposited in bone is comparatively less.

Bone-soft tissue interface

Since density of bone is high so production of secondary electrons is also higher, thus dose deposited in soft tissue near to interface area is higher.

Similar phenomenon in the case of air cavity-bone interface, air cavity-soft tissue interface, and vice versa is seen.[17,18]

The density of frequently used materials for dosimetry and components of human body is as shown in Table 1.[1,19,20]

Table 1 shows density, atomic number, and electron density of various materials where it can be clearly seen that electron density varies in all the materials by a significant number, hence most of the phantoms which are currently in use do not represent the actual human body.

Table 2 compares the density of some organs of goat and human, where density of each organ was calculated with the help of Hounsfield units (HU) measured from TPS and HU-density conversion formula $H = 1000.((\rho/\rho_w) - 1.0)$.[21]

We can see in above table that density of respective organs of human and goat are approximately same. So using the mentioned head and tissue phantom for primary study was a good choice and similar artificial phantom will be very useful in such kind of dosimetry.

Tables 3-6 show the measurements and results of this study. Figure 3 shows the graphical comparison of % variations between planned and measured doses in all four kind of experiments.

Conclusions

Dose verification measurements for modern radiotherapy techniques (3DCRT, IMRT, and image-guided radiation

Table 1: Number of electrons per gram of various materials

Material	*Density (g/cm^3)*	*Atomic number Effective atomic number*	*Number of electrons per gram*
Slab phantom "SP34 phantom (polystyrene (C_8H_8))"	1.045	5.74	3.386×10^{23}
Water	1.00	7.42	3.34×10^{23}
Fat	0.916	5.92	3.48×10^{23}
Muscle	1.00	7.42	3.36×10^{23}
Air	0.001293	7.64	3.01×10^{23}
Bone	1.85	13.8	3.00×10^{23}

Table 2: Mass density of some organs of human and goat

Organ	*Human (female/28 years)*		*Goat (male/1+years)*	
	Density (g/cm^3)	*Volume*	*Density (g/cm^3)*	*Volume*
Eye lens	1.1	0.1	1.135	0.3
Eye vitreous body	1.026		1.024	
Eye layers (retina, choroid, sclera)	1.065		1.072	
Eye		9.6		10.5
Skull	2.423		1.973	
Mandible	2.516		2.253	
Brain	1.052	1336.5	1.065	91.2
Cerebrospinal fluid	0.987		0.985	
Muscle	1.052		1.08	

Table 3: In 3DCRT plans % variation between planned dose on treatment planning system and measured dose on linear accelerator using head phantom

Plan no.	*Algorithm*	*Energy (MV)*	*No. of fields*	*Measured dose (cGy)*	*Planned dose (cGy)*	*% variation*
1	AAA	6 15	1 (CP)+1 (NCP) 1 (CP)	190.33	185.9	2.38 (+)
2	AAA	6 15	4 (CP) 1 NCP)	202.14	207.4	2.54 (-)
3	AAA	6	4 (CP)	190.95	197.3	3.22 (-)
4	AAA	6	2 (CP)+1 (NCP)	172.56	176.0	1.96 (-)
5	AAA	6	4 (CP)+1(NCP)	194.67	191.94	1.42 (+)
6	AAA	6 15	3 (CP) 1 (NCP)	189.14	195.72	3.36 (-)
Mean						2.48
SD						0.74

3DCRT: Three-dimensional conformal radiotherapy, SD: Standard deviation, AAA: Anisotropic analytical algorithm, CP: Coplanar, NCP: None-CP,MV: Mega voltage

Table 4: In IMRT plans % variation between planned dose on treatment planning system and measured dose on linear accelerator using head phantom

Plan no.	*Algorithm*	*Energy (MV)*	*No. of fields*	*Measured dose (cGy)*	*Planned dose (cGy)*	*% variation*
1	AAA	6	4 (CP)+1 (CP)	196.79	193.1	1.91 (+)
2	AAA	6	4 (CP)+1 (NCP)	200.29	203.3	1.48 (−)
3	AAA	6	5 (CP)	204.09	209.5	2.58 (−)
4	AAA	6	6 (CP)+1 (NCP)	190.37	195.0	2.38 (−)
5	AAA	6	7 (CP)	189.2	197.1	4.01 (−)
6	AAA	6	7 (CP)	207.12	201.32	2.88 (+)
7	AAA	6	3 (CP) +4 (CP, 2 fields at each gantry position)	182.02	177.3	2.66 (+)
8	AAA	6	1 (CP) +6 (CP, 2 fields at each gantry position)	198.19	201.2	1.50 (−)
9	AAA	6	2 (CP) +10 (CP, 2 fields at each gantry position)	151.71	155.8	2.53 (−)
10	AAA	6	2 (CP) +12 (CP, 2 fields at each gantry position)	196.59	193.4	1.65 (+)
Mean						2.36
SD						0.77

IMRT: Intensity modulated radiotherapy; SD: Standard deviation; AAA: Anisotropic analytical algorithm; CP: Coplanar; NCP: None-CP,MV:Mega voltage

Table 5: In 3DCRT plans % variation between planned dose on treatment planning system and measured dose on linear accelerator using tissue phantom

Plan no.	*Algorithm*	*Energy (MV)*	*No. of fields (all CP)*	*Measured dose (cGy)*	*Planned dose (cGy)*	*% variation*
1	AAA	15	2	207.56	212.8	2.47 (−)
2	AAA	15	4	219.12	225.6	2.87 (−)
3	AAA	6 15	2 1	311.84	302.45	3.10 (+)
4	AAA	6 15	2 3	208.91	201.87	3.49 (+)
5 (junction plan)	AAA	6 15	4 1	184.69	193.6	4.60 (−)
6 (junction plan)	AAA	6 15	2 1	187.70	197.94	5.17 (−)
Mean						3.62
SD						1.05

3DCRT: Three-dimensional conformal radiotherapy; AAA: Anisotropic analytical algorithm; CP: Coplana,MV: Mega voltage

therapy (IGRT)) were carried out using head (goat head) and tissue (goat meat) phantoms. The results of these measurements were comparatively higher than the results of routine dose verification using commercially available phantoms and some results are higher than tolerance limit ($< \pm 3\%$) prescribed in ICRU 83. This study makes a strong case to develop radiation dosimetry methods based on real human body and also to develop an artificial phantom which should truly represent the interior of human body.

Table 6: In IMRT plans % variation between planned dose on treatment planning system and measured dose on linear accelerator using tissue phantom

Plan no.	*Algorithm*	*Energy (MV)*	*No. of fields (all CP)*	*Measured dose (cGy)*	*Planned dose (cGy)*	*% variation*
1	AAA	6	4+6 (2 fields at each gantry position)	238.25	247.20	3.62 (−)
2	AAA	6	7	193.87	199.4	2.77 (−)
3	AAA	6	7	259.81	253.30	2.57 (+)
4	AAA	6	10 (2 fields at each gantry position)	238.14	245.80	3.12 (−)
5	AAA	6	14 (2 fields at each gantry position)	244.97	257.60	4.90 (−)
6	AAA	6	14 (2 fields at each gantry position)	253.14	260.10	2.68 (−)
7	AAA	6	18 (2 fields at each gantry position)	283.90	292.7	3.01 (−)
8	AAA	6	2+14 (2 fields at each gantry position)	237.51	246.83	3.78 (−)
Mean						3.31
SD						0.78

IMRT: Intensity modulated radiotherapy; SD: Standard deviation; AAA: Anisotropic analytical algorithm; CP: Coplanar; MV: Mega voltage

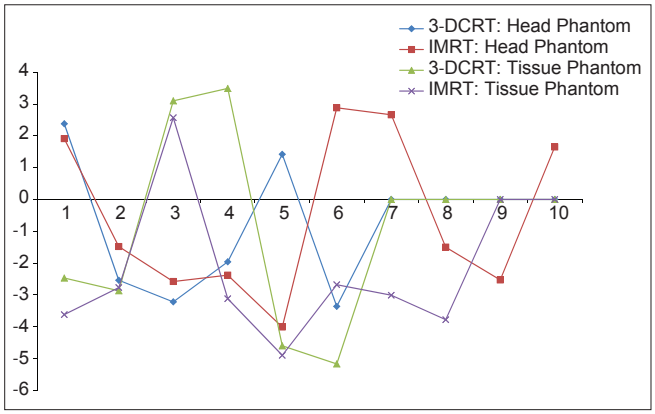

Figure 3: Graphical comparison of % variations between planned doses (on treatment planning system) and measured doses (on linear accelerator) in four types of measurements viz. three-dimensional conformal radiotherapy plans using head phantom, intensity modulated radiotherapy plans using head phantom, 3DCRT plans using tissue phantom, and IMRT plans using tissue phantom

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