SMGroup

Evaluating Radiation Doses for Treating Indigenous Phantoms of Various Weights Under Helical Tomotherapy and Volumetric Modulated Arc Therapy Using Axesse Linac for Lung Cancer

Hsien-Chun Tsenga[1,3], Wen-Shan Liu[1,3,4] and Chien-Yi Chen[2]*

[1]Department of Radiation Oncology, Chung Shan Medical University Hospital, Taiwan

[2]School of Medical Imaging and Radiological Sciences, Taiwan, Republic of China

[3]School of Medicine Chung Shan Medical University, Taiwan, Republic of China

[4]Department of Radiation Oncology, Kaohsiung Veterans General Hospital, Taiwan

*Corresponding author: Chien-Yi Chen, Department of Medical Imaging and Radiological Sciences, Taiwan, Republic of China, Tel: 886-4-928-661433; Email: chien.ccy@gmail.com

ABSTRACT

This investigation is the first in which 10 to 90 kg tissue-equivalent phantoms are utilized as patient surrogates to measure skin (peripheral) Doses **(D_{skin})** of Axesse linac in Volumetric Modulated Arc Therapy and thus to derive a simple equation for Effective Dose **(E)** in normal organs in patients who are undergoing helical Tomotherapy **(TOMO)** to treat lung cancer.

Five tissue-equivalent and Rando phantoms were utilized to simulate patients with lung cancer. E and the equivalent dose for organs or tissues (D_T) were measured using Thermoluminescent Dosimetry **(TLD-100H)**. The TLD-100H device was calibrated using 6 MV photons, and then inserted into the phantom at positions that were close to those of the organs and tissues of interest; then, was measured TLD using a Harshaw 3500 TLD reader. The mean D_{skin} for the lung cancer for one fraction (7 Gy) that was underwent VMAT was evaluated. Both E and D_T were evaluated using ICRP 60 and 103. The E of these phantoms was in the range 3.38±0.64 (10 kg) to 8.76±1.40 (90 kg) mSv/Gy of TOMO treatment. Notably, E decreased exponentially as the phantom weight

increased. The values of D_{skin} varied greatly among positions close to the center of the tumor. The D_{skin} values of the phantoms ranged from 0.51±0.08 (10 kg) to 0.22±0.03 (90 kg) mSv/Gy. These findings are useful for patients, physicians, radiologists and the public.

INTRODUCTION

The Medical Linear Accelerator **(linac)**, Helical Tomotherapy **(TOMO)** (Hi-Art TomoTherapy, Inc., Madison, WI, USA) and Axesse (Eleka Inc, Maryland, USA) at the Department of Radiation Oncology, Chung Shan Medical University Hospital (CSMUH), provide photon energies with accelerating voltages of 6 MV. TOMO can deliver Intensity-Modulated Radiotherapy **(IMRT)** using a fully integrated image-guided radiotherapy system with on-board Mega-Voltage Computed Tomography **(MVCT)** capability. TOMO is a technically advanced method for delivering radiation therapy, favoring conformal and precise treatment [1-3]. Axesse provides photons with accelerating voltages of 6 MV for use in Volumetric Modulated Arc Therapy **(VMAT)**. VMAT has been demonstrated to be a powerful method technique for irradiating many treatment sites with high dose conformity to the tumor, while reducing intra-fraction motion by reducing delivery times [1-3].

Patients are exposed to significant amounts of undesirable radiation during treatment, primarily in the form of out-of-field radiation as a result of scattering and leakage. With growing interest in the use of high-energy photon beams at CSMUH, detailed measurements of extra radiation must be made to estimate the Effective Dose **(E)**, and Equivalent Dose for the Organ or Tissues **(D_T)** and the accompanying skin (peripheral) dose, D_{skin}. To the best of the authors' knowledge, no investigation has compared the E and D_T values that are provided by TOMO and Axesse for patients of various weights with lung cancer [2-5].

Quantitatively measured E and DT values in patients with different body weights can be used to determine the safety of radiation and to revise plans for treating lung cancer. Indigenous tissue-equivalent phantoms with body weights of 10-90 kg as patient surrogates are utilized herein to assess the E and D_T values in various parts of the anatomy. Thermoluminescent dosimetry (TLD-100H, 3.0×3.0×1.0 mm^3; Harshaw, OH, USA) was inserted into patients during oncological treatment. The extra radiation that accompanies is estimated to estimate the D_{skin} for patients.

MATERIALS AND METHODS

Tissue-Equivalent Phantom

Indigenous Polymethylmethacrylate **(PMMA)** phantoms of various weights were utilized to evaluate E and D_T [6-8]. PMMA phantoms were based on GSF- Forshungszentrum fur Umwelt und Gesundheit, (Germany) adult mathematical models and lung masses were based on the ICRP

reference man. These phantoms, developed by ICRU 48 were used as patient surrogates and calculated radiotherapeutic exposures to external photon rays and the Monte Carlo method. The 10 to 90 kg PMMA phantoms were based on a general human design each comprised 31 sections with thicknesses of 1.6 to 3.6 cm, representing the head, neck, torso, abdomen and pelvis, but not arms or legs [7-9]. Through each section was drilled a hole of diameter 11 mm to enable the insertion of TLDs in the position of each organ. The lung tissue-equivalent physical density was 0.296 g/cm^3 ; the skeleton-cortical-bone tissue-equivalent physical density was 1.486, and the skin tissue-equivalent physical density was 1.105 g/cm^3 [7-9]. (Table 1) presents the dimensions and physical properties of Rando and tissue-equivalent phantoms [7].

Table 1: Dimension and physical properties of Rando, tissue-equivalent phantoms.

Phantom	Rando		Tissue-equivalent				
Weight (kg)[1]	70		10	30	50	70	90
Height (cm)[2]	94.5		50	78	84	93	112
Weight (kg)[2]	34.5		6.75	19.0	31.5	44.1	57
cm slices[-1]	2.5		1.6	2.3	2.7	3.0	3.6

The Rando phantom (Alderson Radiation Therapy Phantom, Radiology Support Devices, Long Beach, CA) with a height 175 cm and a mass of 73.5 kg, which comprises polyurethane, a human skeleton and soft lung tissue, is suitable for measuring doses of what are utilized in oncology [6,7]. (Figure 1) presents the outer appearances of five tissue-equivalent and Rando phantoms.

Figure 1: Use five tissue-equivalent and Rando phantoms as patient surrogates.

Calibrate TLD-100H Using 6MV Beams

For subsequent photon dose measurement and linearity calibration, the TLD-100H chips were calibrated using 6 MV beams of linac at CSMUH. Calibrated TLDs were irradiated at doses in the range 10-1100 cGy, which includes the prescribed daily fraction dose. To ensure the homogeneity of each batch of TLD, the TLDs were irradiated in a manner consistent with the International Atomic Energy Agency recommendations (TRS-398) by placing five solid water phantom (SWP) slabs, each with an area of 30×30 cm^2 and a thickness of 10 mm, to enable and reach electronic equilibrium and by placing above them in an SWP using a Skin-Source Distance **(SSD)** of 100 cm and a 10×10 cm^2 field [7,10]. A Farmer-type NE 2571 ionization chamber (Nuclear Enterprises, UK), which had a volume of 0.6 cc, was placed in the solid water according to a method that can be found elsewhere [4,6].

CT Simulation and Treatment Plan

All simulations of Computed Tomography **(CT)** examinations with phantoms were carried out using a 16-slice CT sim (GE Aquillion 64; Toshiba Medical Solutions, Japan) at CSMUH. The CT-based simulation was carried out using phantoms that were lying in the supine position. Lung treatment plans by that involved Axesse and TOMO linacs were developed and then reviewed by medical doctors and senior radiotherapists, all of whom had ten years of experience [2]. A lung tumor (3×3×3 cm^3) was simulated at a depth of 5 cm in the central part of the lung of a 70 kg phantom. Marks on the skin were made in three directions. **(Figures 2a, b, and c)** present the TOMO treatment plans and isodose distributions in the 10 kg tissue-equivalent phantom.
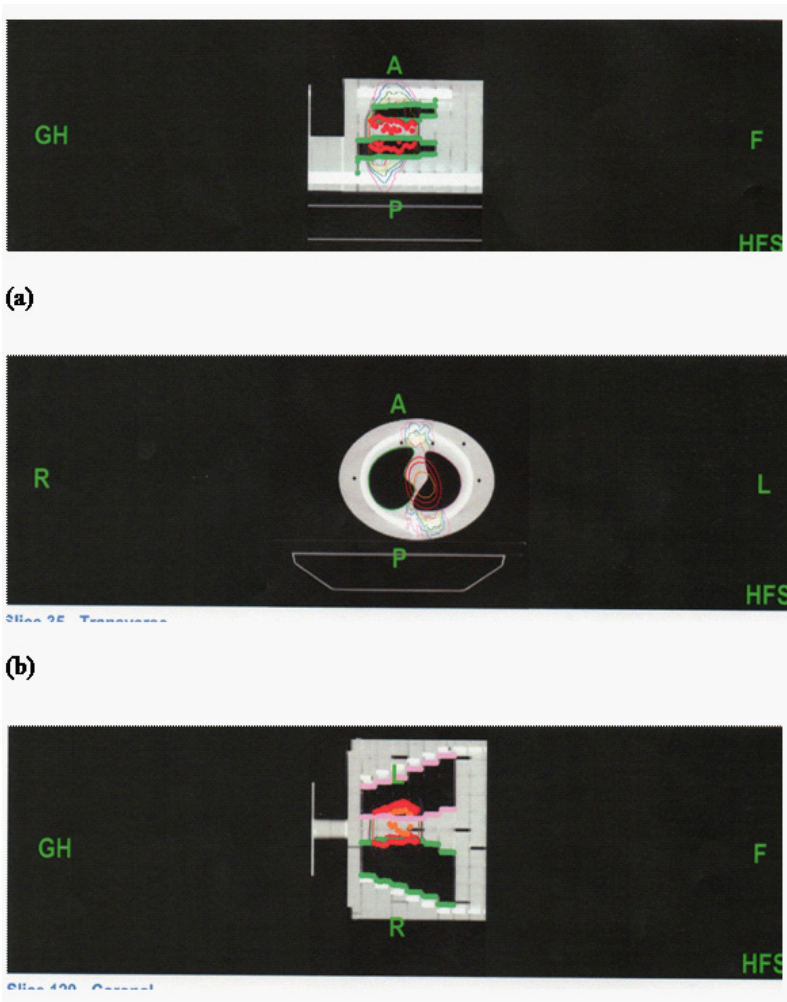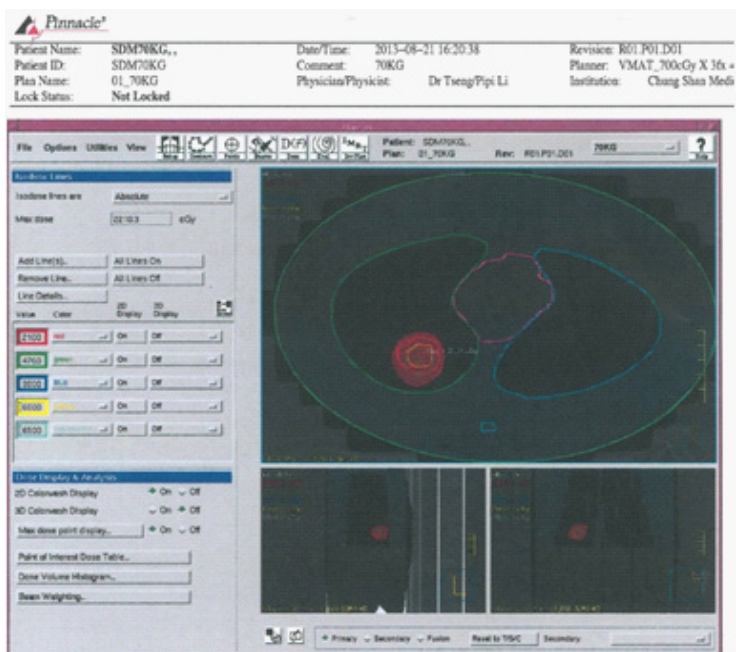
Figure 2: a, b, and c show the TOMO treatment plans.

The CT images and organ contours were transferred to linac. The prescribed dose was determined from the Planned Target Volume **(PTV)**. Complete prescribed photo doses (200 cGy) of 6 MV were in red on the image and delivered to the PTV of the phantom in a single treatment. The protocol required a total tumor dose of 70 Gy for lung cancer treatment.

Figures 3(a): presents the treatment plan of that is generated using the Pinnacle planning system (Philips Radiation Oncology System, Fitchburg, WI, USA) for a 70 kg phantom.
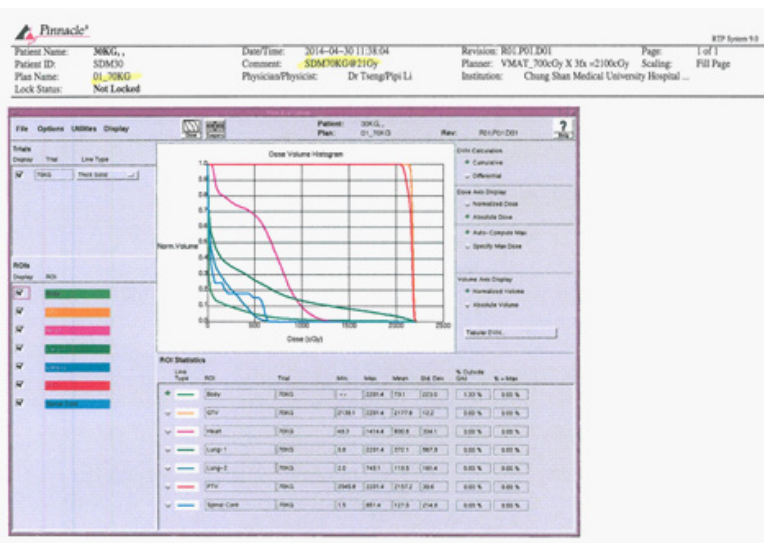

Figure 3(b): plots isodose distributions for a 30 kg tissue-equivalent phantom.

The CT images and organ contours were transferred to the VMAT of Axesse linac. The prescribed dose was specified at the Planning Target Volume **(PTV)**. Complete prescribed photo doses (700 cGy) of 6 MV are shown in red and delivered to the PTV of the phantom in a single treatment. The protocol required a total tumor dose of 21 Gy to treat lung cancer. Following exposure, TLDs were removed from the phantoms to be read subsequently. The organs at risk are the heart (red); lung 1 (green); lung 2 (blue); spinal cord (cyan). The prescribed isodose (21 Gy) is shown in red.

Evaluation of E and DT of organ or Tissue, T

The ICRP committee has been quantifying personal radiation doses for several decades. In 2007 the ICRP 103 made an announcement in which the protection quantity for personal dosimetry is E [11]. W_T (a weighting factor) was used for the mean absorbed in a tissue or organ T. E is defined as the summation of the weighted equivalent doses in 19 critical organs and "remainder" of the body, as specified in (Table 2), and given by the following.

$$E = \sum_T W_T \cdot H_T \qquad (1)$$

$$H_T = \sum_R W_R \cdot D_T \qquad (2)$$

The unit of D_T is J kg^{-1} or Sievert (Sv). ICRP 103 recommended W_T values for 19 specified organs and five remainder organs. W_T has been demonstrated to be broadly applicable to adult and children although the best method for assessing risk in radiative oncology requires knowledge of D_T and age-specific organ risk factors [11]. The measurements made using each TLD-100H were easily converted into specific equivalent photon doses for the represented D_T, since each TLD-100H was well calibrated under similar calibration conditions in preliminary measurement (cf. Table 2).

Table 2: Locations of the 47 measurement points, the weighting factors (W_T) for various internal organs or tissues are recommended by ICRP 103 and adopted for evaluating E (cf Eqs. 1 and 2)

Organ	Measurement points	ICRP 103	W_T	Number of TLD
Thyroid	Thyroid	0.04	0.04	3
Brain	Brain	0.01	0.01	3
Salivary	Salivary	0.01	0.01	3
	Red bone marrow		0.12	
	Clavicle vertebrae		0.04	3
	Thoracic vertebra		0.04	3
	Thighbone femur		0.04	6
Lung	Lung	0.12	0.12	12
Skin	Skin	0.01	0.01	31
Esophagus	Esophagus	0.04	0.04	6
Breast	Breast	0.12	0.12	9
	Bone surface	0.01		
	Clavicle bone, clavicle		0.025	3
	Thoracic vertebra		0.025	3
	Rib		0.025	9
	Thighbone		0.025	3
Liver	Liver	0.04	0.04	15
Colon		0.12		
	Ascending		0.03	3
	Transverse		0.03	3
	Descending		0.03	3
	sigmoid flexure		0.03	3
Stomach	Stomach	0.12	0.12	6
Bladder	Bladder	0.04	0.04	3
Gonads	Testes	0.08	0.08	3
Remainder		0.12		
	Lens		0.017	6
	Herat		0.017	3
	Pancreas		0.017	3
	Spleen		0.017	3
	Kidney		0.017	3
	Small intestine		0.017	3
	Prostate (male)/ uterus (female)		0.017	3
Total		1.000	1.000	154

Evaluation of Dose for Organ or Tissue

ICRP 103 recommended the locations of 47 points for measuring doses along with the number of TLDs and the W_T for the practical evaluation of E of various internal organs or tissues [6,11]. E has been determined for 14 critical organs, namely [1] the brain, [2] the salivary glands, [3] the thyroid, red bone marrow (including [4] clavicle vertebrae, [5] the thoracic vertebra [6] and the thigh bone and femur), [7] lungs, [8] skin, [9] the esophagus, [10] breasts, bone surfaces (including [4] clavicle vertebrae, [5] the thoracic vertebra [6] the thigh bone, femur [11] and rib), [12] the liver, [13] the colon, (ascending, transverse, and descending) [14] the stomach, [15] the bladder, and [16] the gonads. The remainders are [17] the lenses, [18] the heart, [19] the pancreas, [20] the spleen, [21] the kidney, [22] the small intestine, and [23] the prostate (male)/ uterus (female) [11]. In this investigation, TLDs were fixed in holes in the PMMA and Rando phantoms. Each hole was identified by the number of the organ with which the hole was associated. The doses that were absorbed by various phantom organs were obtained from the doses at the reference points, where measurements were made directly using TLDs [6,7]. A total of 31 measurement positions were utilized on the anterior central line, and are marked as 1-31 in (Figure 4).

Figure 4: 70 kg Phantom with marked TLD measurement positions.

Each slice has its own $D_{skin, i}$. The mean D_{skin} (i = 1-31) of the ith slice was computed, and D_{skin}, i was substituted into Eq. 3. D_{skin} was determined by summing the D_i of all scan slices, with each weighted by its absorbed dose.

D_{skin} was thus obtained using the equation,

$$D_{skin} = \frac{\sum D_{skin,i}}{31} \quad (i = 1{\sim}31) \qquad (3)$$

where $D_{skin, i}$ is the dose of that is absorbed by each slice in the phantom [6].

Following treatment, the measurements made using the TLDs were analyzed using a fully automated Harshaw 3500 reader (Solon, OH, USA) and a readout was obtained following a two-step procedure, which consisted of heating to 50 °C and holding for 1 s, and then heating to 240 °C at a rate of 10 °C /s and holding for further 1 s, as described elsewhere [2,7,10-12].

In Vivo Measurement During Radiative Oncological Treatment

In vivo measurements of primary irradiation were made firstly in the lung, skin and nearby organs and then throughout the body. A total of 154 TLDs were inserted into the phantom and used to evaluate directly the $_{DT}$ of slices 11-13 of the normal lung. Parts of the lung outside the PTV during lung therapy were considered the lung dose, D_{lung} [6,8,12].

Sensitive organs and tissues in the phantom were located by comparison with anatomical cross-slices. $_{DT}$ values that were measured at several points at a constant distance from the central axis using TLDs in the same organ were averaged to obtain a representative response of that organ and the averaged equivalent doses at that distance were used (cf Table 2). For large-volume organs, such as the breast and stomach, many several TLDs were placed in each slice. The mean doses of the breast and stomach were denoted as D_{breast} and $D_{stomach}$, respectively. The mean dose of the gonad was D_{gonad}. The error bars in (Figure 4) represent uncertainty in the D_T values that were measured using various TLDs in a single organ/tissue. The final D_T was obtained by averaging three TLDs in each bag [2,7,12]. Nine TLD chips were used to measure the background radiation in the our laboratory.

RESULTS

Calibration

To determine the photon dose and *E* for linear calibration, the TLDs were irradiated using 6 MV photons at CSMUH. TLD measurements were made five times using each of randomly selected TLDs. The conversion factor for the TLD-100H was Y (mSv) = 0.0767 + 0.0347 ×TLD (nano coul), and the square of the correlation coefficient (R^2) was 0.9988 [7]. The corresponding relative error is attributable to variations in density of phantom, the attenuation of epoxy-resin, and PMMA, which was used in the tissue-equivalent phantom (cf Figure 1).

Measurement Uncertainty

The precision and accuracy of TLD-100H in the estimating radiation dose are functions of several parameters. The sources of errors that affect the precision and accuracy in determining the E can be found elsewhere [6,7,13]. The total uncertainty, 3 to 10%, was dominated by seven factors (A), and dominated by TLD counting statistical errors; it was effectively eliminated by performing five independent trials. (B) Systematic uncertainties may have arisen resulted from the TLD calibration of 6 MV photons response dose-associated nonlinearity, which caused 8 to 10% fading of the TLD signal. (C) The temporal variations of the Harshaw 3500 reader that was used in this study yielded systematic uncertainties from 10% to 12% [5]. (D) An additional uncertainty of 5% to 10% was included for measurements in organs on the periphery of the investigation volume, to account for uncertainty in the positions of the volume relative to large or small organs as well as skin. (E) Errors in the power fluctuation from the TOMO and Axesss linac were obtained based on monthly clinical quality assurance (QA) reports to be within ±2%. (F) The uncertainty that arose from non-tissue-equivalence effects in the tissue-equivalent phantom was set to 5%, because these phantoms were constructed entirely based on recommendations in ICRU report 48 [8,9]. (G) The uncertainty in WT was set to 5% because WT was normalized (cf Eq. 1) [5,6,11,13]. TLDs display linearity, reproducibility, and accuracy herein. The density effect was estimated by generating a digital homogeneous or heterogeneous phantom that is similarly exposed to 6MW photons using Monte-Carlo simulation [7,13].

Based on 47 measurements (cf Table 2), estimates of the peripheral dose of Axesse at any point in phantoms with various body weights were made. (Figures 5(a)-(g)) plot peripheral dose leakage as a function of measured over a total of five trials based on distance from the irradiated center of the tumor in these phantoms. Peripheral doses were normalized independently to 100% of the dose at the center of the tumor for each phantom. The peripheral dose outside the scan field varied significantly, decreasing as the distance from the center of the tumor increased.
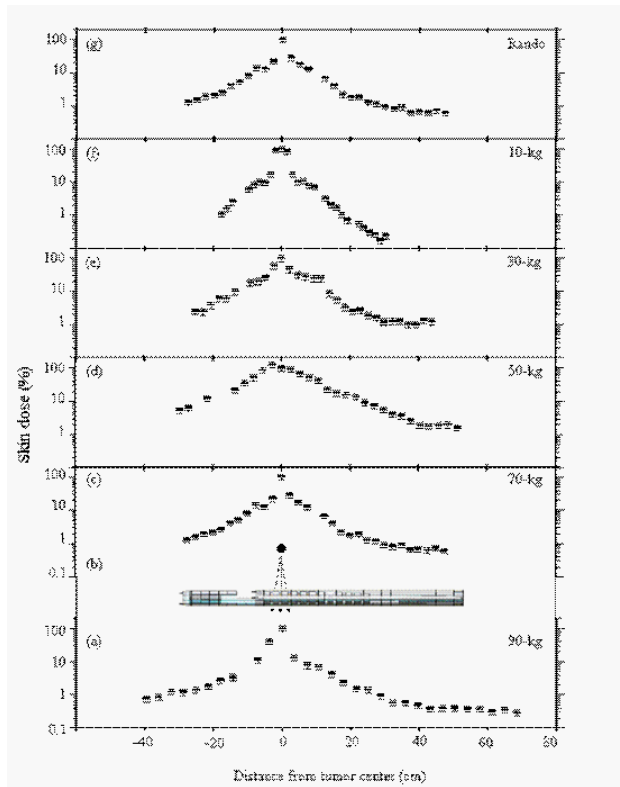
Figure 5: Assessing the D_{skin} (mSv/Gy) as a function of lateral distance (cm) form center of tumor during Axesse treatment for lung cancer; (a) 90 kg (b) 70 kg irradiation, TLDs inserted into the phantom, (c) 70 kg, (d) 50 kg, (e) 30 kg, (f) 10 kg and (g) Rando phantoms.

Effective Dose of TOMO

The value of *E* for lung cancer treatment using 6 MV linac was large, reaching up to 6.92±1.25 mSv/Gy for the Rando phantom and 9.44±1.70 (10 kg), 7.94±0.15 (30 kg), 7.63±1.37 (50 kg), 6.37±1.15 (70 kg), 4.58±0.83 (90 kg) mSv/Gy for the tissue-equivalent phantoms.

E (mSv/Gy) = 10.0-0.0564×M (kg), R^2 = 0.97877 (4)

where *E* is in mSv/Gy, and M represents the mass of the tissue-equivalent phantom in kg [7]. Figure 6 compares values of *E*. The *E* of the Rando phantom was 6.92±1.25 mSv/Gy, which is approximately 1.086 times that of the 70 kg phantom, which was 6.37±1.15 mSv/Gy. The difference between the *E* of the Rando phantom and that of the 70 kg phantom was 8.63%. The large deviation was related to density. Both *E* and D_T in this investigation are consistent with those obtained elsewhere [2-6].
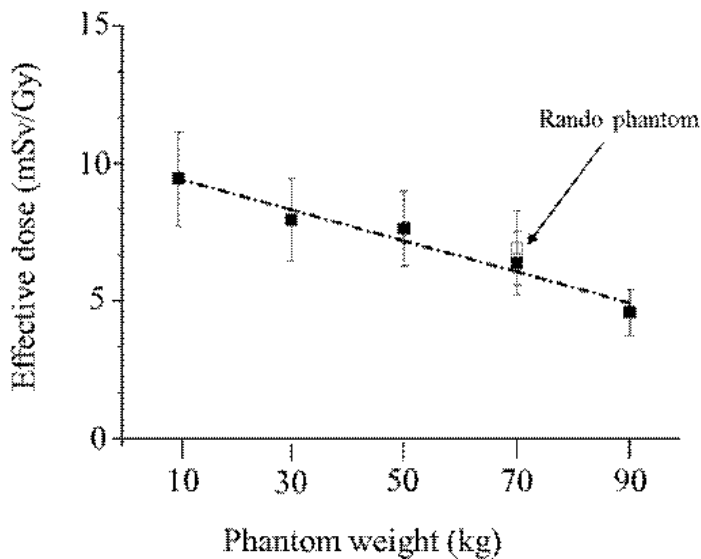
Figure 6: Estimated effective dose (mSv/Gy) in TOMO treatment of lung cancer.

Average values and spread over various TLDs are shown (bars). Notably, E decreased as the weight of the phantom increased. The in vivo measurements reveal that the peripheral doses depend on phantom weight. The 10 kg phantom has a relatively high E and D_T because the organ/tissue is close to the center of the tumor. The internal peripheral dose is significant close to the tumor center, but becomes negligible at distances of greater than 40 cm. Skin doses (D_{skin}).

Based on 31 measurements, estimates were made of D_{skin} (peripheral dose) phantoms with various body weights. (Figures 7 (a) to (g)) present the *in vivo* D_{skin} based on distance from the center of the irradiated tumor in these phantoms, averaged over a total of five trials. D_{skin} was normalized independently to 100% of the dose at the center of the tumor in each phantom. Moreover, D_{skin} outside the scan field varied significantly, decreasing with distance from the center of the tumor. Notably, contribution of the $D_{skin, 14}$ from the 14th slice of the Rando phantom fell remarkably from 100% to 7.73%.
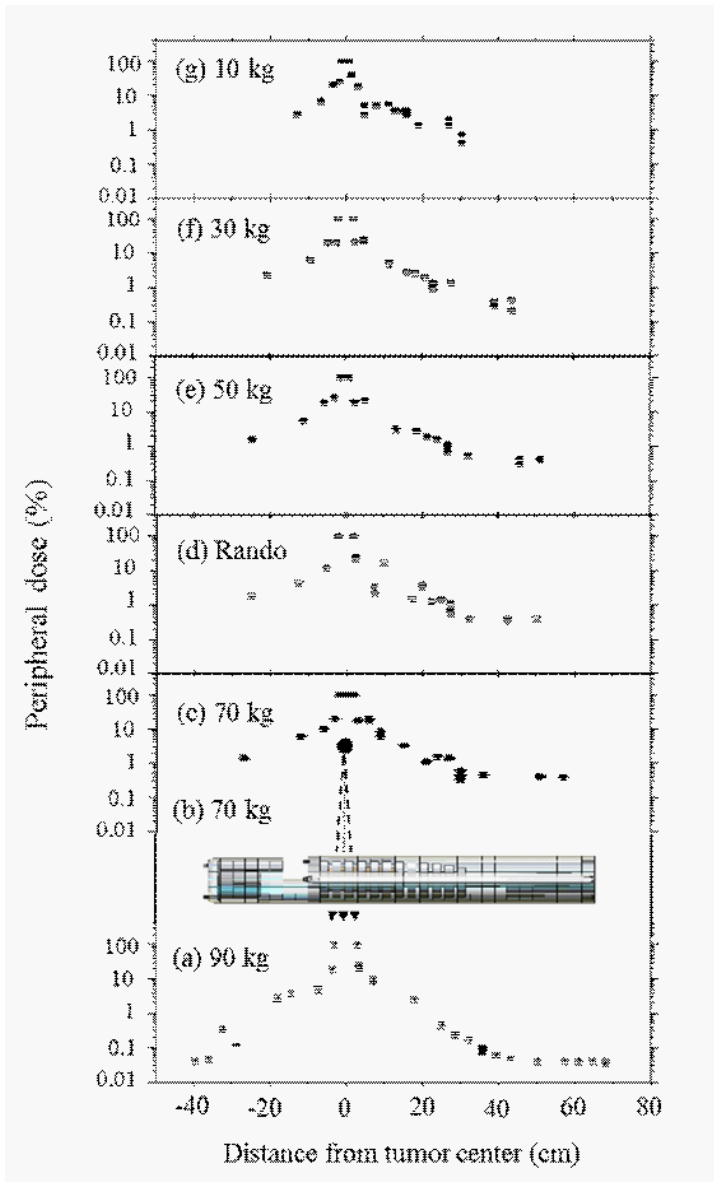
Figure 7: Assessing peripheral doses (%) as a function of lateral distance (cm) from the center of tumor during treatment of TOMO for lung cancer; (a) 90 kg, (b) 70 kg irradiation, TLDs inserted into phantom, (c) 70 kg, (d) Rando (e) 50 kg, (f) 30 kg, and (g) 10 kg phantoms.

Estimating Equivalent Doses for Normal Organs in TOMO Treatment

A high D_T was obtained in the thoracic, lung, breast, and collar bone during TOMO treatment for lung cancer (Figure 8). D_{thor} was measured in slice 13 in each phantom. D_{thor} was highest in tissue-equivalent phantoms mean D_{thor} = 20.7±4.32, with a range from 29.1±4.64 (10 kg) to 15.4±2.93 (90 kg) mSv/Gy. In fact, in the aforementioned organs, a small difference in the positions of the

TLDs may result in one or a few TLDs near a tumor center. The thyroid, brain and gonad had relatively low D_T values.

The D_{lung} for lung cancer treatment upon exposure to 6 MV linac was high, reaching up to 21.2±3.78 mSv/Gy for the Rando phantom and 25.3±4.01 (10 kg), 24.0±3.81 (30 kg), 21.8±3.96 (50 kg), 19.6±3.55 (70 kg), and 15.3±2.89 (90 kg) mSv/Gy for tissue-equivalent phantoms, respectively. Most patients who are treated with radiation are worried about their gonads, which are believed to be much more sensitive to radiation than other organs [7,11]. The mean equivalent dose to the gonads, D_{gonad}, was 0.48±0.09 mSv/Gy (range, 0.74±0.12 (10 kg) to 0.33±0.06 (90 kg) mSv/Gy). The 50, 70, 90 kg, and Rando phantoms had very similar Dgonad values because the gonads are a large distance from the center of the tumor. This finding agrees closely with that of D'Agostino, who found that the mean dose was 0.47 mSv/Gy (range, 0.42 to 0.70 mSv/Gy) in the head and neck regions, which are 70 cm from a prostate cancer, during TOMO treatment [2].
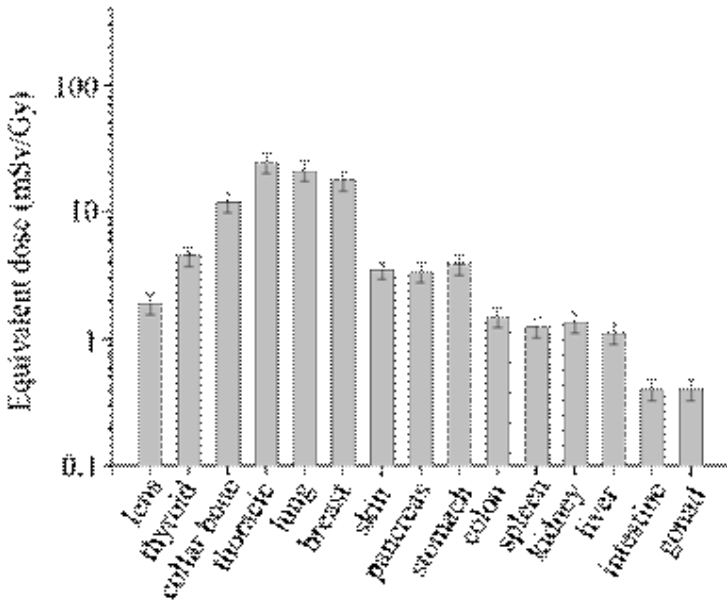

Figure 8: Equivalent dose (mSv/Gy) in Rando phantom. TLDs are inserted in a high-dose region. A high equivalent dose is found close to tumor center.

The different results are attributable to differences in (A) treatment modalities, (B) distances of TLDs from the center of tumor (C) methods of measurement and (D) linac performance. Other differences may arise from inconsistencies in density between tissue-equivalent and the anthropomorphic phantoms used herein, despite the fact that the specified densities (0.296 g/cm^3 for the lung, 1.486 g/cm^3 for the skeleton-cortical-bone and 1.105 g/cm^3 for skin) of the tissue-equivalent phantoms are close to those of the Rando phantom. These phantoms and the TLD method are useful and reliable for estimating E, D_T, and D_{skin}.

CONCLUSION

This investigation assesses the relationship between body weight and E for tissue-equivalent phantoms that are undergoing radiotherapy to treat lung cancer. The analytical results reveal that E (mSv/Gy) is 10.0-0.0564×M (kg), where M is the mass of the tissue-equivalent phantom (kg) in TOMO therapy. Clearly E decreases as body mass increases. Notably, D_T was highest close to the center of the tumor and decreased as the distance from the center of the tumor increased. D_{skin} differs measurably among the phantom on account of extra peripheral radiation.

High D_T values were obtained in the thoracic, lung, breast, and collar bone. Skin closer to the center of the tumor receives a higher dose. The calculated $D_{skin, i}$ clearly reveal that D_{skin}, decreased as distance from the center of the tumor increased. These analytical results reveal that the TLD-100H method has high sensitivity and stability. *In vivo* D_T measurements reveal that the tissue-equivalent phantoms, designed using ICRU 48, are reliable for evaluating E and extra peripheral radiation. The quantitative results provide practical insights into radiation protection.

ACKNOWLEDGMENT

References

1. Jia MX, Zhang X, Yin C, Feng G, Li N, Gao S, Liu da W. Peripheral dose measurements in cervical cancer radiotherapy: a comparison of volumetric modulated arc therapy and step-and-shoot IMRT techniques. Radiat Oncol. 2014; 9: 61.

2. D'Agostino E, Bogaerts R, Defraene G, de Freitas Nascimento L, den Heuvel FV, et al., Peripheral doses in radiotherapy: A comparison between IMRT, VMAT and Tomotherapy. Radiation. Measurement. 2013; 57: 62-67.

3. Kim DW, Chung WK, Shin D, Hong S, Park SH, Park SY, Chung K. Risk of second cancer from scattered radiation of intensity-modulated radiotherapies with lung cancer. Radiat Oncol. 2013; 8: 47.

4. Mutic S, Low DA. Whole-body dose from tomotherapy delivery. Int J Radiat Oncol Biol Phys. 1998; 42: 229-232.

5. Kry SF, Salehpour M, Followill DS, Stovall M, Kuban DA, et al. Out-of-field photon and neutron dose equivalents from step-and-shoot intensity-modulated radiation therapy. Internal Journal of Radiation Oncology Biology Physics. 2015; 62: 1204-1216.

6. Tseng HC, Liu WS, Tsai HH, Chu HY, Lin JB, Chen CY. Radiation dose for normal organs by helical tomotherapy for lung cancer. Appl Radiat Isot. 2015; 102: 35-41.

7. Tsai SY, Chen CY, Chen JC. Evaluating Effective Dose for Indigenous Phantoms with Different Weights Undergoing Computed Tomography Examination for Coronary Artery Calcium. IEEE Transactions on Nuclear Science. 2013; 60: 2147-2154.

8. International Commission on Radiation Units and Measurements. ICRU report 48: Phantoms and computational models in therapy, diagnosis and protection, ICRU. 1992.

9. Matsumoto T. Monte Carlo simulation of depth-dose distribution in several organic models for boron neutron capture therapy. Nuclear Instrumental and Method in Physics Research A. 2007; 508: 552-557.

10. Tanir G, Cengiz F, Bolukdemir MH. Measurement of dose given by Co-60 in radiotherapy with TLD-500. Radiation Physics and Chemistry. 2012; 81: 355-357.

11. International Commission on Radiation Protection. ICRP, Recommendations of the International Commission on Radiological Protection Technical Report ICRP-103. 2007.

12. Kawaura C, Aoyama T, Koyama S, Achiwa M, Mori M. Organ and effective dose evaluation in diagnostic radiology based on in-phantom dose measurements with novel photodiode-dosemeters. Radiat Prot Dosimetry. 2006; 118: 421-430.

13. Chu KH, Lin YT, Hsu CC, Chen CY, Pan LK. Evaluation of effective dose for a patient under Ga-67 nuclear examination using TLD, water phantom and a simplified model. J Radiat Res. 2012; 53: 989-998.