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THE EFFECT OF TISSUE HETEROGENEITY ON DOSE DISTRIBUTION INSIDE RANDO® WOMAN HETEROGENEOUS PHANTOM

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ABSTRACT: Human body organs and tissue have different values of density. The nature of interaction between radiation and organs is not the same due to differences in density of medium, and energy and type of radiation. Low density medium has high range of energetic radiation inside the medium with low values of mass attenuation coefficient. Treatment plan considers the densities of human tissues and organs like water density, so readings of predicted doses inside body have no accurate outputs. The use of real dosimetry inside human heterogeneous phantom gives answers of these differences. TLD-100H has high sensitivity for radiation doses than other TLD types and can be reused but it cannot keep signals after annealing procedures to get one signal by the use of Harshaw® TLD reader.

KEYWORDS: dosimetry, heterogeneity, MammoSite, radiation, treatment planning.

INTRODUCTION

Dosimetry is the practical part of measuring or calculating absorbed doses in a medium. In MammoSite balloon brachytherapy (MBS) which is used in breast cancer radiotherapy; it is used to determine dose distribution by the use of radioactive sources (Ir^{192}) inside surrounding tissues to plan for acceptable dose distributions, calculate patient doses, and to provide a prescription dose system [1]. Dosimetry in brachytherapy is becoming increasingly more important due to recent improvement in brachytherapy techniques enabling more accurate dose defining by the use of remote afterloading, CT scan data, MRI for volume definition, the use of low energy gamma radiation sources, and the possibility of real time biological and dosimetric optimization which has led to improve the accuracy of dose distributions and dose calculations in tissue equivalent materials to modify the algorithms [2]. Nucletron Oncentra is one of the treatment planning systems used for brachytherapy uses water based dosimetry which assumes a homogeneous medium by which a full scatter of radiation exists, this assumption may causes an errors due to the heterogeneous nature of human body which has distribution of different tissue densities [3].

The human body has heterogeneous compositions. The average densities of human organs and tissues have different values of 0.26, 0.89, 1.02, and 1.12 $g.cm^{-3}$ for lung, fat, soft tissue, and bone respectively [4].

THE INTERACTION OF RADIATION WITH TISSUES AND ORGANS

To understand photon interaction with different organs and tissues; some different items should be presented for organs and tissues, such as the effective atomic number (Z_{eff}), an energy dependent parameter due to its varying value with photon energy, and mass attenuation coefficient (μ/ρ) that identifies the number of scattered photons by coherent and incoherent interactions, or absorbed photons by photoelectric effect, pair or triple production, and photonuclear interactions by the target tissue, and effective electron density [5]. Photon with high energy transfers part of its energy to material. The secondary electron range results from the interaction, depends on incident photon energy and density of material. If electron range for certain energy has a value of x (cm) in water then its values will be ($\frac{x}{\rho}$), where ρ is the density of tissue or organ, for that the range for electron in lung, fat, soft tissue, and bone will be 3.8461x, 1.1236 x, 0.98 x, and 0.892 x respectively. It is clear then that photons and electrons have more range in lung tissues than in muscles or water then photons and electrons have more range in lung tissues than in muscles or water which means that electron radiation energy is absorbed in the more dense tissues close to the radioactive source [7]. Mass attenuation coefficient (μ/ρ) for lung tissue at average Ir^{192} radiation energy (0.38MeV) has a value of 0.10778 $cm^2.g^{-1}$, but it has a value of 0.1086 $cm^2.g^{-1}$ for water, mass energy-absorption coefficient, μ_{en}/ρ for lung tissues is 0.03235 $cm^2.g^{-1}$, and for water is 0.032616 $cm^2.g^{-1}$ [6].

The probability of photoelectric interactions depends on the atomic number (proportional to Z^3), which increases with increasing atomic number. Low photon energies and high atomic number of materials increase the probability of photoelectric interactions. On ther hand, materials with a significant proportion of hydrogen which have more electrons per gram enhance the probability of Compton interactions. In photoelectric interaction, tissues capture all photon energy, whereas in Compton interaction only a portion of its energy is absorbed [7]. Ir^{192} emits gamma radiation with energies extended from 0.1 to 1.1 MeV, so lower energy photons interact via photoelectric effect with atomic electrons then disappears, but for intermediate energy photons; Compton effect is the way for photon to lose some of its energy to atomic electron in the medium and continue in a new direction, then total attenuation coefficients consist of the previously mentioned interactions [7]:

$$\mu_{(total)} = \mu_{(photoelectric)} + \mu_{(Compton)} \tag{1}$$

MAMMOSITE BALLOON BRACHYTHERAPY

A new technique for partial radiotherapy is the MammoSite balloon HDR Ir^{192} brachytherapy, by which the balloon must be in contact with lumpectomy cavity surfaces with minimum 7 mm balloon surface to skin distance [8]. It is a fast and effective treatment method in early stages of breast cancer by the use of HDR Ir^{192} or electronic brachytherapy [9], and a modality for delivering radiation to the tumor in achieving local control due to the minimal toxicities and cosmetic outcomes [10]. The dose reduction for the smallest balloon is 9% compared to 12% for the largest balloon [3]. MammoSite RTS is simple for both physician and patient, by which the balloon surface conforms to the target. Tumor size, breast characteristics, and location and geometry of the lumpectomy cavity must be taken into consideration before treatment procedure [11].

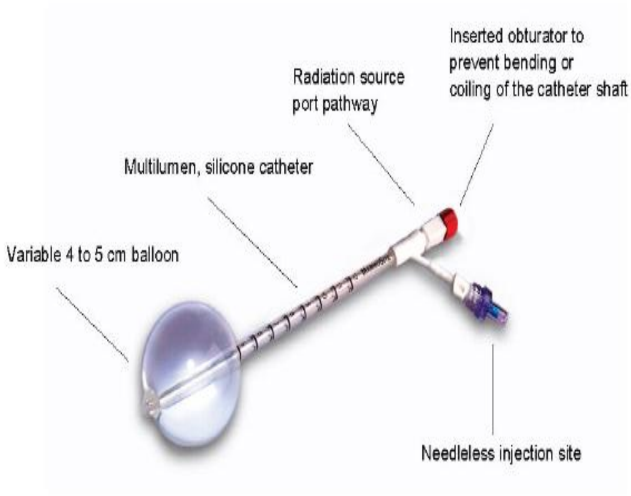

Fig.1: MammoSite balloon catheter [13]

This method is used after surgery by the use of intermediate radioactive source to kill any residual cancer cell surrounding the lumpectomy cavity; a balloon catheter is inserted inside the breast into the lumpectomy cavity and inflated with saline to stay there during the treatment period of not more than 5 days. A radioactive source with high dose rate (HDR) by afterloader machine (HDR unit) enters its centre to deliver a precise amount of dose to surrounding tissues around the balloon [13]. Five-year outcomes of MammoSite balloon brachytherapy concluded breast cosmetic outcome, low late toxicity, and excellent control of residual cancer cells [14]. MammoSite balloon catheter device insertion into lumpectomy cavity is easier than interstitial catheters and has only one entry side. However the risk of local infection may be increased due to the balloon placement [15]. Factors like the balloon volume after inflation, the symmetry of balloon, the conformance of cavity to the applicator, and the balloon-skin distance must be considered within MammoSite brachytherapy [11].

DOSIMETRY

TLD-100H was chosen in the current study because of its high sensitivity and linearity to doses, low rate of fading, with good stability through a number of readout cycles, and tissue equivalent effective atomic number (Z) to represent the contribution of photons energy. Its sensitivity is 30-40 times higher than other TLDs. The readout protocol has a maximum temperature of 300°C, but some additional traps do not appear at this temperature. During radiation; the radiation induced population of the electron traps above Fermi level. To reuse the TLD, it is annealed in a furnace to allow the mobilization of holes and electrons in traps to the equilibrium positions. During readout, thermal energy is used to empty the trap to release photons of visible light in the process. The readout process is done using Harshaw 3500® [16].

TREATMENT PLANNING

The planning target volume (PTV) for MBS is defined as the volume of tumor bed expanded 1 cm from the balloon cavity placed between the chest wall and pectoral muscle allowing at least 5 mm margin from the skin without the present of seroma or air gap. The region of interest (ROI) is the region within the pectoral muscle, closest ribs, PTV, balloon volume for MammoSite, trapped seroma or air, and the skin surface [17]. Treatment planning system must take into account the effect of tissue heterogeneity and do the needed correction for this factor to make the accuracy to the planned dose distribution by a factor called dose modification factor (DMF), which is the dose rate ratio in homogenous medium at 10 mm depth behind the applicator surface to that of heterogeneous medium at the same distance. Little differences between the reality and planning system causes some differences while the delivery of doses during the treatment, but it may be affect the recurrence of cancer cells if the breast receives an insufficient dose. The distribution asymmetry can be achieved and the dose to skin can be reduced by eliminating or decreasing the dwell time when planning with partial breast irradiation (PBI) if the lumen is very close to surface of the skin, and the absence or lack of backscatter radiation can reduce skin dose. In the plan delivery, a single source traverses each lumen that stops for a planned period of time at each dwell position. If the tissue inhomogeneity correction is lacking in the treatment planning system, the dose in PTV of phantom geometry will be under dose by 7 to 12% and will raise the recurrence in some patients [18]. CT and CT based planning is needed for all patients to achieve the coverage of PTV and fixing the target volume [19]. The accurate planning of the target and more information about organs and organs at risk of the patient raise the possibility of conformal radiation by which the prescribed dose reaches the target with low radiation risk to surroundings and lower necrosis or fibrosis due to high dose [20].

MATERIALS AND METHODS

RANDO® woman heterogeneous phantom is divided into number of slices with 2.5 cm thickness. Each slice contains a number of pinholes for placement thermoluminescent dosimeters.

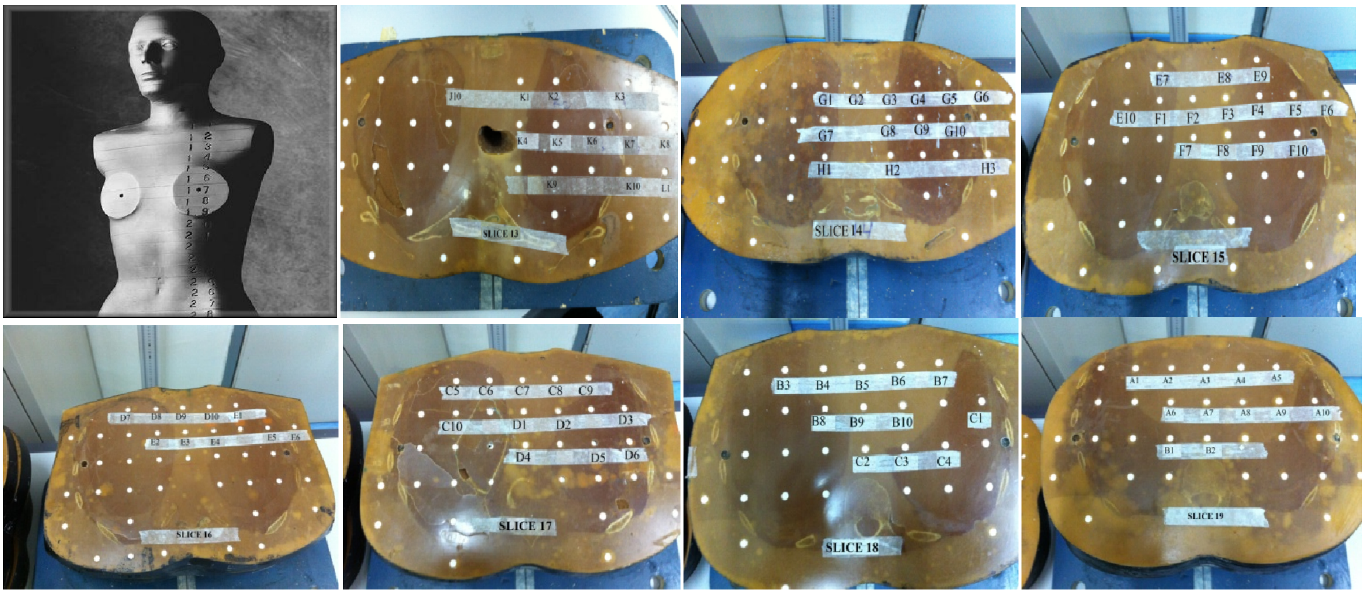

Fig.2: RANDO® phantom and TLD locations inside its pinholes

The vertical distance between centers of two adjacent pinholes is the same as the horizontal distance of 3 cm. Chest region (slices 10 to 23) has ribs, lungs, spine, sternum, and breasts.

The chosen brachytherapy technique is MammoSite balloon brachytherapy system (MBS). A homemade breast was made by mixing equal quantities of paraffin wax and beeswax [21] to get a mixture with density of 0.93 g.cm^{-3}. Balloon was inserted inside the phantom lumpectomy cavity and filled with saline to reach a diameter of 5 cm. Pinholes of slices from 13 to 19 were named as A1,…,L1 were placed inside lungs and trunk (soft tissues). CT scan of whole phantom was taken by the use of Philips Brilliance Big Bore CT scan as in figure 3.

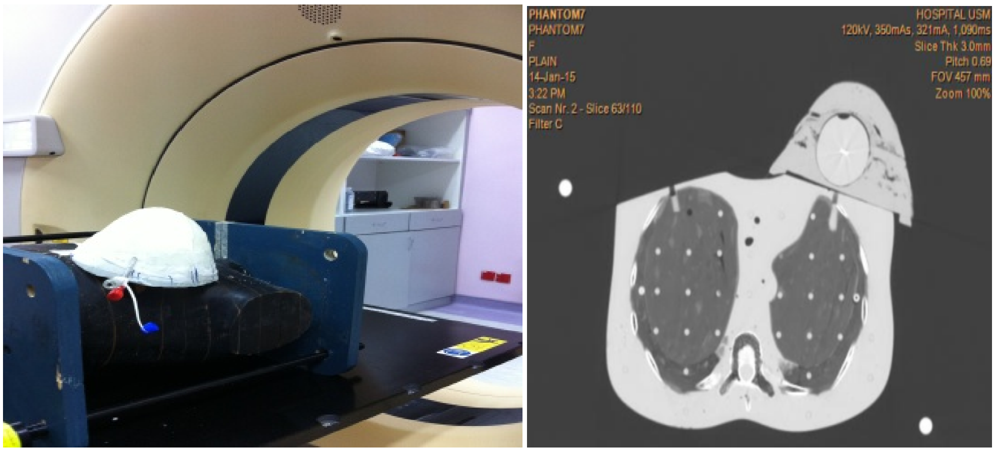

Fig. 3: CT scan for RANDO® phantom with MammoSite balloon inside left breast

Data from CT scan were transferred to treatment planning area to develop a suitable treatment plan by the use of Nucletron Oncentra Master Plan system (TPS). The first step was to define organs of interest (external, lungs, sternum, chest wall, and left breast), applicator, and PTV, then reconstruction of catheter and dwell positions to achieve recommendations of TG-43, and RTOG-0413 protocols. The activation of radioactive source (192-Ir-mHDR-v2) was to deliver 340 cGy for each fraction. MBS has 11 dwell positions with 11 dwell times through a single lumen. The treatment planning program considers a homogeneous phantom with water density (1 g.cm^{-3}).

Doses at TLD locations were measured as live dose option after approving the treatment plan and tabulated in table 2.

TLDs 100H were fixed at its own positions inside phantom slice pinholes. Radiation delivery was carried out using microSelectron v3 treatment unit (mSel v3 (18)) via MammoSite balloon catheter for 3 fractions.

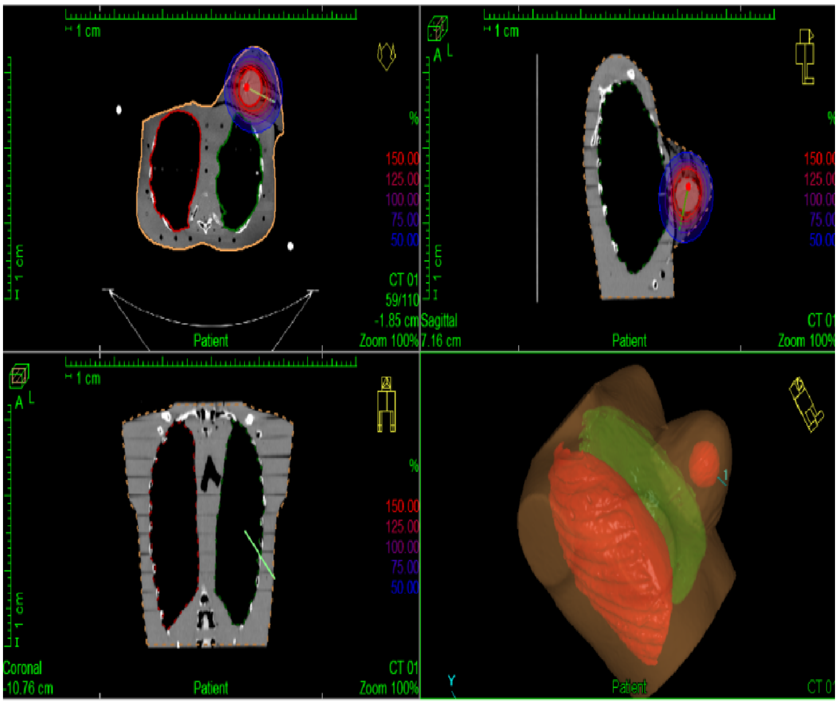

Fig. 4 : Target definition and source activation for MBS treatment plan

TL signals $(\mathrm{TL}(\mu\mathrm{C}))$ were measured by Harshaw® 3500 and doses were calculated using determined factors such as TLD sensitivity, calibration factor $(\mathrm{CF}(\frac{\mathrm{cGy}}{\mu\mathrm{C}}))$, and element correction coefficient (ECC) for each TLD. The TL dose reading $(\mathrm{D}_{\mathrm{TL}}(\mathrm{cGy}))$ was calculated by the use following equation:

$$\mathrm{D}_{\mathrm{TL}}(\mathrm{cGy}) = \mathrm{TL}(\mu\mathrm{C}) \times \mathrm{CF}(\frac{\mathrm{cGy}}{\mu\mathrm{C}}) \times \mathrm{ECC} \tag{2}$$

Doses measured by TLDs were also tabulated in table 2.

RESULTS

Approving treatment plan was done based on recommendations of TG-43, and RTOG-0413 protocols. The recommendations are tabulated in table 1 with MBS output.

Table 1: Treatment plan for MBS and TG-43, and RTOG-0413 protocol recommendations.

Item	Recommendations	MBS
V90	≥ 90% PTV	108%
V150 for normal breast tissue	< 50 cm^3	19.42
V200 for normal breast tissue	< 10 cm^3	5.53
Maximum breast skin dose (%PD)	< 145%	100%
DHI	≥ 0.75	0.736
Dose (per each fraction)	340 cGy	340 cGy
DNR	≤ 0.35	0.264
CI	≥ 0.90	0.941
balloon volume (MSB)	$\leq$ 30%	14%
balloon symmetry	$\leq$ 2 mm	2 mm
balloon-surface distance	$\geq$ 7 mm	16 mm
60% of whole breast volume receives	$\geq$ 50% PD	68.9
V50	< 60% $V_{\text{total organ}}$	* 17% left lung *0% right lung

Treatment plan (TP) for MBS was used to determine doses inside phantom pinholes where the location of TLDs.

Table2: Doses (cGy) to TLD locations inside phantom by treatment plan.

TLD	D(cGy)	TLD	D(cGy)	TLD	D(cGy)	TLD	D(cGy)	TLD	D(cGy)	TLD	D(cGy)
A1	8	B7	105	D7	11	F9	29	I1	25	J9	7
A2	16	B8	15	D9	42	F10	30	I2	55	J10	8
A3	29	B9	25	D10	80	G1	11	I3	31	K1	2
A4	45	C2	15	E4	46	G2	19	I4	15	K2	5
A5	65	C3	23	E6	64	G3	29	I5	16	K3	11
A6	12	C4	28	E7	20	G4	38	I9	14	K4	13
A7	20	C5	12	E8	65	G5	42	I10	17	K5	16
A8	30	C6	21	F1	14	G6	38	J1	18	K6	17
A9	31	C9	15	F2	25	G7	7	J2	16	K7	16
B1	8	C10	8	F3	39	G8	17	J4	33	K8	13
B2	12	D2	48	D9	42	G10	24	J5	8	K9	9
B3	11	D3	70	F6	51	H1	4	J6	12	L1	7
B5	38	D4	17	F7	15	H2	9	J7	15		
B6	64	D5	30	F8	22	H3	11	J8	15		

After using the afterloader to deliver prescribed dose via MammoSite balloon catheter, each TL signal related to a certain amount of dose. Readings were done for three fractions and the average had been taken and tabulated in table 3.

The following TLD locations are inside lung tissues in the phantom: B3, C5, C10, D3, D5, D7, F10, G4, G5, G9, H2, K2, K5, K6, and K9, while others were inside normal tissues at trunk or under rib bones.

Table3: Doses (cGy) measured by exposed TLDs inside phantom.

TLD	D(cGy)	TLD	D(cGy)	TLD	D(cGy)	TLD	D(cGy)	TLD	D(cGy)	TLD	D(cGy)
A1	13.64	B7	186.75	D7	16.55	F8	40.96	H1	11.36	J5	36.58
A2	26.44	B9	25.33	D8	34.28	F9	48.47	H2	26.17	J6	28.19
A3	36.49	C2	28.76	D9	74.83	F10	45.83	H3	19.34	J7	32.93
A4	75.83	C3	43.03	D10	165.85	G1	21.87	I1	39.30	J8	39.81
A5	90.02	C4	65.95	E4	117.45	G2	31.74	I2	78.94	J9	17.57
A6	17.90	C5	20.82	E6	67.51	G3	55.19	I3	48.82	J10	17.55
A7	38.77	C6	45.04	E8	119.54	G4	69.44	I4	19.95	K1	13.67
A8	52.22	C9	132.33	F1	27.53	G5	74.96	I5	28.04	K2	18.35
B1	9.43	C10	9.38	F2	50.01	G6	40.28	I9	16.31	K3	30.02
B2	20.79	D2	89.89	F3	47.34	G7	14.42	I10	30.55	K4	27.72
B3	18.15	D3	101.66	F5	81.23	G8	29.44	J1	17.69	K5	19.74
B5	67.22	D4	24.76	F6	72.92	G9	51.37	J2	18.97	K6	22.63
B6	128.91	D5	35.24	F7	22.43	G10	29.98	J4	47.06	K7	23.01
L1	9.32	K8	16.03	K9	18.26						

CONCLUSION

Dose values with comparison between treatment plan (TP) and dosimetry by TLD-100H have different values at same pinhole locations inside phantom tissues and organs, and as expected that TP readings have higher values inside lung due to higher attenuation coefficient for water than lung tissues, so the passing electron has more range in lung tissues than water. Soft tissue which has value of μ/ρ near to that of water has readings similar to that of TP.

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