Design and Fabrication of Wax Cube Phantoms for the Assessment of Paraffin Wax as Phantom Material for Radiotherapy

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Abstract

This research is intended to check paraffin wax's suitability and find a cost-effective phantom material for the daily quality assurance of a Medical Linear Accelerator. In our evaluation, we consider paraffin wax as a phantom material and fabricate two phantoms. Among the two phantoms, one containing air bubbles, and another is bubbles free. The phantoms are then irradiated with an Elektra Synergy S Linear Accelerator of photon beam energies 6 MV and 15 MV. The dosimetry property of paraffin wax phantoms has been compared with water phantom by following absolute dosimetry protocols TRS-398 and TG-51.Paraffin wax has been found as good phantom material due to its proximity to water's dose absorption property. For a photon beam of 6 MV, the absorbed dose deviation concerning water phantom changes from -2.7 % to + 1.0 % in the bubble-free phantom case. In contrast, the other phantom deviation varies from -3.4 % to -1.2 %. For 15 MV beam, the deviation is -0.1 % to + 2.4 % and -1.4 % to -3.7 % subsequently. The present study demonstrates that wax phantoms can be locally fabricated and may be used in Bangladesh's cancer centers for routine QA purposes.

Keywords: Phantom, Dosimetry, Absorbed dose, Paraffin-wax, Scaling factor

1. Introduction

Paraffin waxes are predominantly composed of a regular straight chain of hydrocarbons. In chemistry, paraffin is the common name for the alkane hydrocarbon having the general formula C_nH_{2n+2} paraffin wax is related to solids having n=20 to 40. The concrete forms of paraffin called paraffin wax is $C_{20}H_{42}$ to $C_{40}H_{82}$ [1].

Paraffin wax consists of a mixture of hydrocarbon molecules containing carbon atoms, a soft, colorless, stable, and usually derived from petroleum, coal, or shale oil. It is stable at room temperature and starts to liquefy above roughly 37°C [2], and the boiling point of paraffin is above 370°C [3]. Paraffin wax is primarily found as a stable white, odorless, tasteless, waxy, with a particular melting point between about 46 and 68°C [4] and a density of around 900 kg/m^3 [5]. It is insoluble in water, but in ether, benzene, and some esters, it is soluble. The most common chemical reagents do not impact paraffin, but it burns readily [6].

Todiminish the calibration uncertainty of radiation beams, absorbed dose to water for high energy photons and electrons is recommended as the standards and reference absorbed dose by AAPM Report no.51 [7], IAEA Technical Reports no.398 [8] and JSMP Standard Dosimetry for Radiotherapy [9]. In these recommendations, the reference medium is defined as water; however, solid phantoms, which are water substitute materials, are discouraged because they have the most considerable inconsistencies in absorbed dose determinations. Dose distribution in solid phantom can be converted to appropriate dose distribution in water using scaling factors.

Water is recommended as the standard phantom material by the key dosimetry protocols [7, 8, 10, 11] for the dosimetry of high-energy photons and electrons. However, in the Linac or ^{60}Co photon beams, water phantoms are uncomfortable to use because it is challenging and time-consuming to position or align it in the beam. Water phantoms are replaced by solid phantoms [12]in modern cancer clinics. Currently, lots of altered plastic materials are used for dosimetry purposes in radiotherapy and radiation physics departments. For instance, white and clear polystyrene, PMMA, Solid water WT1, Solid water RMI-457, Virtual water, Plastic water, etc., are widely used as solid water phantom materials [13]. Solid phantom materials caused a 3%-4% spread in calculating the dose relative to the value determined from water measurements for all beam energies [14].

The practice of solid phantoms has been well recognized for the dosimetry of photons from brachytherapy sources as well as therapeutic x-ray and electron beams [8, 12,15-17]. The materials of these solid phantoms are also tissue-equivalent or water-equivalent. The solid materials to build these phantoms include solid water, polystyrene, acrylics, and more. But the end product is expensive and needed to be imported from other countries. It will bear advantages if a cheap and locally available tissue-equivalent material is available, especially in a developing country like Bangladesh. Hence, we tried to put readily available low-cost material like paraffin wax on the show, whether it serves this purpose or not. The physical and electron density of paraffin wax is similar to water [4]. Variation of absorbed doses in different solid phantom materials, including paraffin wax, is compared in one investigation [18]. Because of this water-like properties, we decided to fabricate two phantoms using paraffin wax. We also determined correction factors for using this material instead of water. These factors can be used as a correction factor whenever this material other than water is used as a phantom material.

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2. Materials and Method

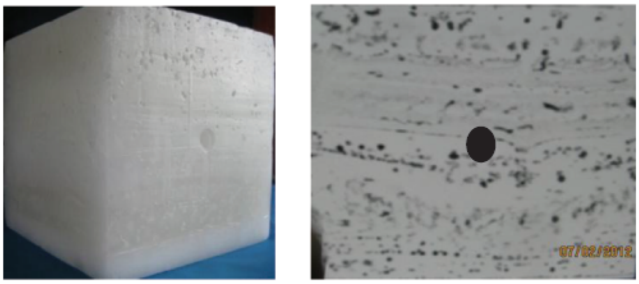
The present study was performed using the radiotherapy facility of Khwaja Yunus Ali Medical College and Hospital (KYAMCH), Enayetpur, Sirajganj, Bangladesh. An Elektra Synergy S Linear Accelerator is produced by Elekta (Elekta Oncology Systems, Crawley, UK) capable of producing three different energies of photon beams (4 MV, 6 MV, 15 MV) and five different electron beam of energies (6 MeV, 8 MeV, 10 MeV, 12 MeV, 15 MeV, 18 MeV) have been used as the source of mono-energetic photon beams of energy 6 MV and 15 MV respectively. The properties of paraffin wax have been shown in table 1.

Table 1: Properties of phantom material

Material name	Chemical Composition	Mass density (gm/cm^3)	Number of Electrons/g ($\times 10^{23}$)
Paraffin wax	$C_nH_{2n+2}(20 \le n \le 40)$	0.88 - 0.92	3.44
Water	H_2O	1.00	3.34

A dice was prepared by cutting a steel sheet and subsequent welding of the resulted pieces in a workshop. The shape of the dice was made perfectly cubical, with each side measuring 20 cm. Any part of the sheet with the rough surface was avoided, and care was taken so that each surface was perfectly flat. To prepare a proper wax cube, melted wax was poured into the dice in the beginning to form a layer of roughly 3 cm and was allowed to be solidified. A similar procedure was repeated seven times to deposit one layer above the other. Finally, a single cubic block of wax, a wax phantom of 20cm × 20cm × 20cm, was acquired.

The fabricated wax phantom was placed in the Philips CT-Scanner [Model no: Philips Brilliance CT 64-channel scanner] of the cancer center of KYAMCH to achieve an internal image. It was found that the wax phantom had many air bubbles. The bubbles' presence may make the block less suitable as a phantom because, for absolute dosimetry, we need water equivalent property for phantom material.



(a) Physical observation (b) CT Image

Fig. 1: Outer side physical observation and CT-Scan image of air bubble containing paraffin wax phantom

Many air bubbles in the customized wax phantom prompted us to develop another phantom that would be bubble-free. Paraffin wax in the form of slabs of dimension 30 × 25 × 4 cm^3 was purchased from the local market. It was cut into a size of 21 × 21 × 4 cm^{3,} and the texture of the surfaces was checked to ensure flatness. The slabs were joined one on top of the other after heating them on a hot plate at 50°C. The cube sides were trimmed and leveled with a sharp special knife, and a phantom of 20 × 20 × 20 cm^3 was obtained. The phantom was then placed in the CT scanner, and the image was taken and found, as presented in Fig. 2.

(a) Physical observation (b) CT Image

Fig. 2: Physical observation and CT-Scan image of air bubble-free paraffin wax phantom

Each of the two phantoms requires to insert of an ionization chamber into the isocenter of a phantom. Therefore, the center of the phantom's surface was located with the help of a measuring scale. A vertical line of length 10 cm would touch the isocenter of the phantom. The phantom was drilled along this vertical line with a Drill machine (d.c.) with great caution, and a hole of length 10.5 cm was made. The extra 0.5 cm was added so that the center of the ionization chamber's active volume coincided with the phantom's isocenter.

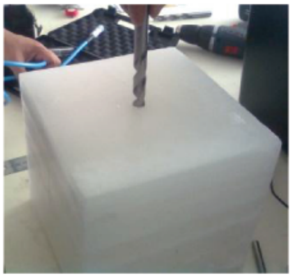


Fig. 3: Preparing hole for ionization chamber insertion

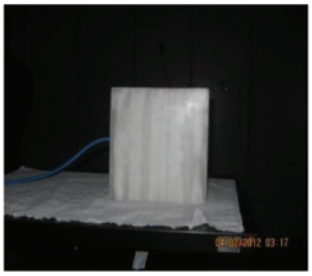


Fig. 4: Experimental phantom setup

The paraffin wax phantom-1 was placed on the couch of the linear accelerator. The phantom surface center was aligned with the beam's central axis from the gantry at a zero-degree angle. The distance between the phantoms surfaces to the source was kept 100 cm using optical mark readers by moving the couch vertically. After positioning the phantom, a Farmer (0.6 cc) type ionization chamber was inserted into the hole. The other end of the ionization chamber was connected to an electrometer. The monitor unit of the linear accelerator was made 100, and the exposure of radiation was started. Then the electrometer readings were taken. The readings were taken three times for each of the 6 MV and 15 MV photon beams. For each energy, readings were taken by placing all the four faces of the cube up. The water phantom was placed on the Linac couch, and readings were taken for 6 MV and 15 MV similarly. The digital thermometer and barometer took the temperature and pressure of all phantoms. Absorbed dose $D_{W,Q}$ to water at the reference depth, z_{ref}, in a water phantom irradiated by a beam of quality Q is [8].

$$D_{W,Q} = M_Q \times N_{D,W} \times k_{TP} \times k_S \times k_{pol} \times k_{Q,Q_0} \qquad (1)$$

Where,

M_Q = Monitor reading.

$N_{D,W}$ = Calibration factor in terms of absorbed dose to water.

K_{TP} = Temperature Pressure correction factor.

K_S = Ion recombination correction factor of an ionization chamber.

K_{pol} = Factor to correct an ionization chamber's response for the effect of a change in polarity of the polarizing voltage applied to the chamber.

k_{Q,Q_0} = Factor to correct for the difference between an ionization chamber's response in the reference beam quality Q_o used for calibrating the chamber and the actual user beam quality, Q.

To define the correction factor for polarity, readings of the electrometer were taken with positive and negative polarity, and for the ion recombination correction factor, readings were taken for two different voltages. In this experiment, absorbed dose based absolute dosimetry protocols TG-51 and IAEA TRS 398 have been followed.

3. Results and Discussion

The ratios between the doses in the water phantom and those in paraffin wax phantoms were determined for both 6 MV and 15 MV and are presented in Table 2 and Table 3. Those ratios are expressed as scaling factors. Scaling factors are obtained from dividing the absorbed dose of water phantom by the absorbed dose in paraffin wax phantom since water is used as a standard for absolute dosimetry [8]. Naturally, this scaling factor is unity for water. The scaling factors for both phantoms are presented in the last columns of Tables 2 and 3. It is observed that the deviation is the least for both energies for the paraffin wax phantom in bubble-free conditions. Nonetheless, the difference is slightly higher this time. Finally, both paraffin phantoms' deviation was found within ± 5% for the photon energies 6 and 15 MV.

Table 2: Scaling factor for two paraffin phantoms of beam energy 6 MV

Name of phantom	Surface no.	M_Q	$N_{D,W}$	$K_{T,P}$	K_S	K_{Pol}	$K_{Q,Q0}$	Dose	Scaling factor
Phantom-1	S-1	12.67	0.05408	1.00218	1.00015	1.00353	0.997	0.6871	1.010
	S-2	12.72	0.05408	1.00218	1.00015	1.00353	0.997	0.6899	1.006
	S-3	13.07	0.05408	1.00218	1.00015	1.00353	0.997	0.7088	0.979
	S-4	13.15	0.05408	1.00218	1.00015	1.00353	0.997	0.7132	0.973
Phantom-2	S-1*	13.04	0.05408	1.00011	1.00015	1.00353	0.997	0.7057	0.983
	S-2*	13.19	0.05408	1.00011	1.00015	1.00353	0.997	0.7139	0.972
	S-3*	13.27	0.05408	1.00011	1.00015	1.00353	0.997	0.7182	0.966
	S-4*	12.98	0.05408	1.00011	1.00015	1.00353	0.997	0.7025	0.988
Water phantom	Up	12.85	0.05408	0.9981	1.00015	1.00353	0.997	0.6941	1.000

Table 3: Scaling factor for two paraffin phantoms of beam energy 15 MV

Name of phantom	Surface no.	M_Q	$N_{D,W}$	$K_{T,P}$	K_S	K_{Pol}	$K_{Q,Q0}$	Dose	Scaling factor
Phantom-1	S-1	14.77	0.05408	1.00218	1.00015	1.00353	0.997	0.8010	1.024
	S-2	14.79	0.05408	1.00218	1.00015	1.00353	0.997	0.8021	1.022
	S-3	15.04	0.05408	1.00218	1.00015	1.00353	0.997	0.8157	1.005
	S-4	15.13	0.05408	1.00218	1.00015	1.00353	0.997	0.8206	0.999
Phantom-2	S-1*	15.37	0.05408	1.00011	1.00015	1.00353	0.997	0.8319	0.986
	S-2*	15.60	0.05408	1.00011	1.00015	1.00353	0.997	0.8443	0.971
	S-3*	15.73	0.05408	1.00011	1.00015	1.00353	0.997	0.8513	0.963
	S-4*	15.46	0.05408	1.00011	1.00015	1.00353	0.997	0.8367	0.980
Water phantom	Up	15.18	0.05408	0.9981	1.00015	1.00353	0.997	0.8199	1.000

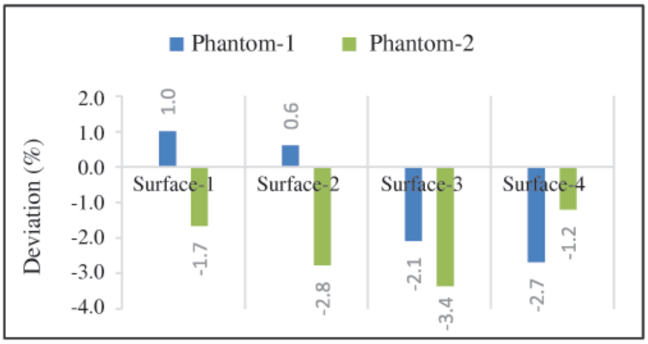


Fig. 5: Dose deviation diagram for both phantoms concerning water phantom for photon beam energy 6 MV

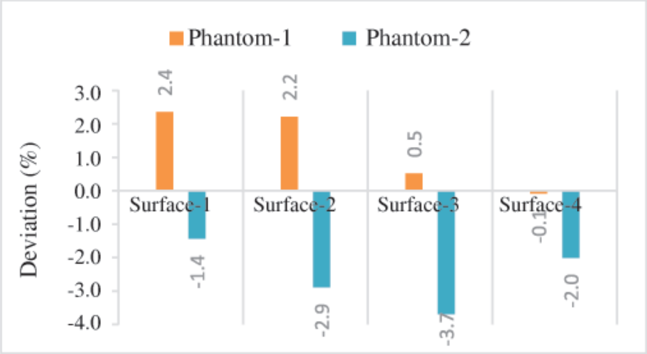


Fig. 6: Dose deviation diagram for both phantoms concerning water phantom for photon beam energy 15 MV

For beam energy 6 MV, the dose deviation diagram illustrates the eccentricity for phantom-1, which varies from + 0.6 % to -2.7 %, whereas for phantom-2, the dose changes from -1.7 to -3.4%. For phantom-1, surface-1, and surface-2 show minimum deviation, and surface-3 and surface-4 exhibit higher value. Conversely, for phantom-2, surface-1 and surface-4 show minimum deviation and surface-2, and surface-3 displays more.

Again, for beam energy 15 MV, the dose deviation corresponding to water varies from–0.1 to +2.4 % for phantom-1, and for phantom-2, values are within – 1.4 to 3.7 %. In phantom-1, surface-4 and surface-3 show excellent agreement with water phantom, but surface-1 and surface-2 differ. It is assumed that the surface to surface variation may be induced due to the chamber tilting inside the phantom. Since the chamber's hole was made with a d.c. Drill machine freehand, it may have caused a slight tilt inside the phantom.

It appears from the deviations' values that paraffin wax shows good agreement in terms of its proximity to water regarding absorption of dose. Using paraffin wax instead of water makes the least deviation in dosimetry. Though the dose variation in some surfaces has considerably fluctuated, this value is within the acceptable limit, i.e., within ± 5%, declared in many standard guidelines [7, 8].This deviation may be due to the chamber hole prepared for the cylindrical (Farmer type) ionization chamber insertion. Since the center of the cube (phantom) was considered the measurement point, the center may have slightly tilted due to the manual drilling process. Moreover, while the preparation costs of a bubble-free paraffin wax phantom of proper dimensions are only $ 200, on the other hand, the minimum price of any solid water phantom is about $ 10000, which is much more expensive for a country like Bangladesh. The structure of the phantom may suffer from the deformity.

Consequently, the chamber hole may get contracted in form factor, in case of any increase in temperature, putting its durability into question. The problem can be easily mitigated using a plastic frame and a dummy ionization chamber to provide structural strength. Thus the life span of the phantom can be significantly increased. It is recommended for the absolute dosimetry to keep the solid water phantom in the linear accelerator room to avoid the temperature fluctuation in a different place of the radiotherapy center [19].

Although the deviations of absorbed dose from that in water phantom are not negligible for solid phantoms [20], the cancer clinics in Bangladesh do not make any correction while using these solid phantoms. In the daily quality assurance of the machine output in the clinics, the scaling factor should be used as a correction factor for solid phantoms. It is demonstrated that the phantom we made is reasonably good, but for more perfection, further experiments are required. The outcomes showed that the material used in our study could be utilized in the construction of the cube phantom and can be used in cancer clinics in Bangladesh for routine QA purposes.

4. Conclusion

Two paraffin wax cubephantoms were designed and fabricated in this study to measure the absorbed dose to water and demonstrate that wax phantoms can be locally fabricated for absolute dosimetry, which represents an acceptable and practical alternative to solid water phantom. The dosimetry property of wax has been compared with those of solid water phantoms in place of water phantoms that are usually seen in cancer clinics. The deviations of the measured values for different wax phantom surfaces were compared to the water phantom and found within the acceptable range. In some cases (surfaces), slightly higher deviations were found, which necessitates the scope of further justification regarding these materials and the precision of the phantom's design. A better prototype of phantoms may be fabricated by following the same dimensions, and a chamber shape hole may be generated by drilling vertically in a workshop to eliminate the chamber inclination. We recommend any dose differences between a solid phantom and a water phantom should be quantified before the solid phantom's clinical use. Some steps may be taken in the future to prolong the lifespan of these phantoms, even after its rugged routine use in clinics. Since these locally fabricated phantoms will be readily available and much cheaper (approximately 200 dollars) than the imported and expensive solid phantoms, they may be useful for radiotherapy QA in a developing country like Bangladesh. It is expected that other establishments could also generate their phantoms for regular clinical application by following the methodology and phantom materials used in our study.

Acknowledgment

I would like to express my gratitude to Md. Mahfujur Rahman and Meher Nigar Sharmin, Department of Radiation Oncology, KYAMCH, would find it challenging to complete the research work without their help.

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