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Verification of Depth Dose Curves Derived on Beeswax, Paraffin and Water Phantoms Using FLUKA Monte Carlo Code

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Abstract

This study aimed on the investigation of depth dose curves from beeswax, water and paraffin phantoms using FLUKA Monte Carlo code. In order to test the validity of FLUKA code, computational values of depth doses in water, beeswax and paraffin have been obtained using this code. The relative average coefficient of variation of percentage depth dose was observed to be less than 0.38% between beeswax and water, below 0.2% between water and paraffin and 0.98% between beeswax and British Journal of Radiology supplement 25 data. The deviations of percentage depth doses within the beeswax phantom material were also calculated and it was concluded that, among the treatment fields, the average coefficient of variation was about 0.74% for 7 × 7 cm^2 and 1.23% for 20 × 20 cm^2. The minor deviation in percentage depth dose obtained in this work demonstrates that beeswax phantom has a potential to provide a better alternative material for dose calculations, and hence can be used as substitute material for *in-vivo* dosimetry in external beam radiation therapy using Theratron Equinox 80 Cobalt-60 unit.

Keywords: FLUKA, Monte Carlo code, beeswax, percentage depth dose, phantom

Introduction

In recent years, various technological developments have been made to improve dose delivery accuracy in external beam radiation therapy (EBRT). For this to be possible, one of the requirements is the calibration of radiotherapy machines in terms of photon energy and field sizes used for specific cancer treatment. For a given cancer treatment modality, additional requirements have to be met to ensure that accurate treatments are received by the patients. These include determination of tissue equivalent depth dose curves used in treatment planning and to ensure that deviations between the prescribed and the delivered doses to the target volume are within the ± 5% range as recommended by the International Commission on Radiation Units and Measurements (ICRU) (IAEA 2000, Thwaites 2013, ICRU 2016). It is well established that depth doses measured in water phantom for various field sizes differ (Buzdar et al. 2009, Araki et al. 2017, Hasan et al. 2019). What is not well known is whether these depth doses are the same as the depth doses in human tissues. Implicitly, the use of depth doses measured in water in dose planning protocol is considered to be close to tissue equivalent material because of its absorption coefficients, mass attenuation and comparable effective atomic number (Aslam et al. 2016, Brkic et al. 2016). This equivalence ensures that the prescribed dose which is tissue based is the same as planned dose. For the planned dose to be the same as the delivered dose, the phantom used needs to have dosimetric properties close to those of water over diagnostic and therapeutic ranges (Hartmann Siantar et al. 2001, Ramaseshan et al. 2008, Araki 2017). Since water cannot be molded to desired patient shape and size, other materials including polystyrene, acrylics, polymethy methacrylate (PMMA), plastic water diagnostic therapy (PWDT) and other materials are used in construction of commercial water equivalent phantoms (Akbar et al. 2014, Safigholi and Song 2018). However, the uses of these phantoms to assess dose delivery are hampered by the fact that it is impractical to place the diode detector at the desired position to determine the dose delivered. For this reason, some studies have used paraffin (Rahman et al. 2018) and beeswax (Vidal and Souza 2012) to resolve this problem. Implicitly, using these materials to determine dose delivery accuracy was based on the assumption that they are water equivalent.

The aim of this study is to verify the depth dose curves derived on beeswax, water and paraffin phantoms which are tissue equivalent materials by using FLUKA Monte Carlo (MC) code.

Materials and Methods

Monte Carlo simulation

For this study, a MC code, FLUKA version 2011.2x.7 was used to perform all dose calculations. FLUKA is one of the available simulation codes suitable for modeling dosimetric radiation spectra, which consists of a wide range of energy spectrum (Ferrari et al. 2005). FLAIR installed version 2.3-0 which is an advanced user-friendly interface for FLUKA was used to visualize and editing the simulation geometries (Vlachoudis 2009). These simulations are based on the treatment plans for cancer patients using the available Theratron Equinox 80 tele-cobalt machine manufactured by Theratronics, Canada. This is an isocentric machine with 80 cm source-to-axis distance (SAD) and source diaphragm distance (SDD) of 45 cm.

MC simulation process and treatment fields

The geometry of the phantom was constructed in FLUKA as a rectangular paralellopiped (RPP) of dimension 40 cm × 40 cm × 40 cm (Figure 1). The interface between the phantom and the shielding materials (lead, tungsten and air in the unshielded case) was placed at $Z = 0$ cm. The phantoms were extended from minimum value of Z-axis (Z_{min}) to maximum values (Z_{max}) according to the required field sizes and phantom to be simulated.

A beam of 1.33 MeV was characterized for isotropic emission from Co-60 source in which the scoring plane for a phantom was defined as front surface of RPP and the width of the phantom using SAD of 80 cm. The photon beam was directed to the phantom under investigation in the positive Z-direction and attenuated in a respective phantom. In the present simulation geometry, X_{min} (Y_{min}) and X_{max} (Y_{max}) were selected according to the required field sizes. This results in length and breadth of the target material with different thicknesses defined by Z_{min} and Z_{max}.

In order to improve the accuracy and reduce errors of the simulated results, particle histories of 10^6 photons from the Co-60 source were generated and simulated for each tissue equivalent phantom used in this study. The size of energy binning used was 25 bin enable to generate the simulated values for water, paraffin and beeswax phantoms. Majority of transport parameters in the simulation description were set according to the required values used in real situation for Co-60 teletherapy unit. The four open square fields of sizes 7 × 7 cm^2, 12 × 12 cm^2, 15 × 15 cm^2 and 20 × 20 cm^2 were used in the simulation. The simulations were done using the Pavilion Hewlett Packard Intel Core i5 2.30 GHz, 8 GB random access memory computer, in high-performance mode.

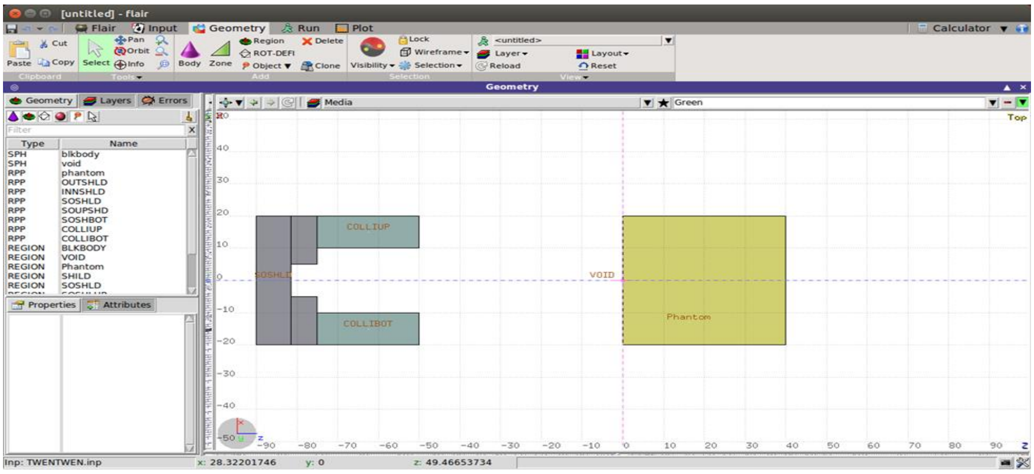


Figure 1: Simulation setting geometry of the phantom with dose scoring regions.

Acquisition of simulated data was done, FLUKA's USRBIN and USRBDX scoring cards were used to calculate energy deposition and to score particle fluence in each stage of simulation by using the auxiliary programs available in FLUPRO to merge the output data (Ferrari et al. 2005). Setting of the phantom in the geometry interface was kept at a distance of 80 cm away from the Co-60 source for effective particles scoring.

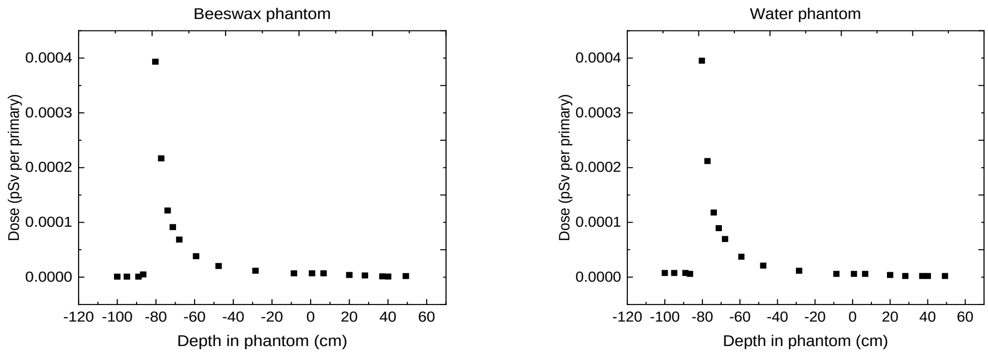
Equivalent dose and depth dose matrices

The dose calculations in water, beeswax and paraffin phantoms were performed using FLUKA code. The code simulates the photons transport in a Cartesian volume and scores the energy deposition in the defined energy bins. The tissue equivalent phantoms in three dimensions were taken depending upon the radiation field size, so as to maintain the accuracy due to scattering and to save the calculation time. For each simulation, particle information recorded was set to *DOSE-EQ* in the *AUXSCORE* input file card and the ambient dose equivalent (*AMB74*) was used as the dose conversion factor for the purpose of this simulation. Data from the simulations were used to extract the dose along the central axis at various depths for the field sizes used. This information is important for analyzing and developing the depth-dose curves and dose profiles in 2D and in 1D projection formats. The low and high energy cut-off for photon was 1.0 MeV and 2 MeV, respectively. The number of histories simulated from phase space depends upon the field size and phantom volume, which was of 2.5 × 10^6 to 5 × 10^6 to achieve the realistic accuracy. Finally, the depth dose calculated at each point from radiation beam combined in a dose matrix enables the plotting of percentage depth dose (PDD) curves.

Results and Discussions

Beam profile comparison

The effect of photon beam of Co-60 teletherapy machine on the dose curves in homogenous phantoms for water and beeswax is presented and discussed in this part. Figures 2 (a) and 2 (b) compare the relative central axis dose of the beeswax and water tissue equivalent materials. The center of the phantom was modeled to be along the central axis of the beam. The central axis dose depositions by using open beam field sizes of 12 cm × 12 cm were obtained as shown in Figures 2(a) and 2(b).



2 (a) 2 (b)

Figure 2: Relative central axis dose for water and beeswax phantoms as a function of depth at 80 cm SAD.

Dose profile comparison shown in Figures 2(a) and 2(b) shows that the beeswax and water data have good agreement with each other. The dose profile has difference of up to 1.5% between these materials in open field technique used during irradiation process. The maximum dose in both settings in Figures 2(a) and 2(b) was observed to be at z = –80 cm, the location of the radiation source in the tele-cobalt unit as modeled during the simulation process.

2 Dimension dose distributions

A 2D view of the photon beam interaction with beeswax phantom is shown in Figure 3, where photon fluence (pSv/primary) is in the *y*– *z* plane at *x* = 0. It can be seen from Figure 3 that the distribution of photon flux of the incident beam are scattered in all directions where the higher dose concentrated at a depth of z = 0 cm in which the maximum dose was expected to fall. The relative dose distributions in the central plane were normalized to the maximum dose (2 Gy).

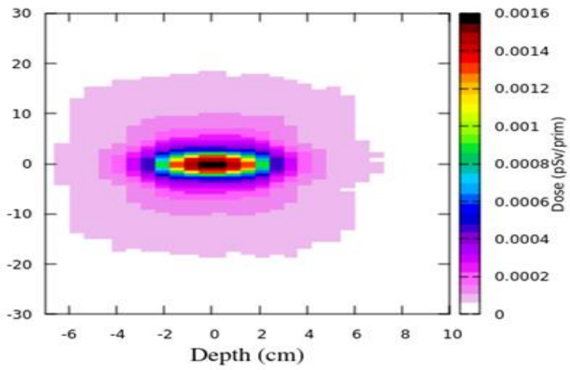


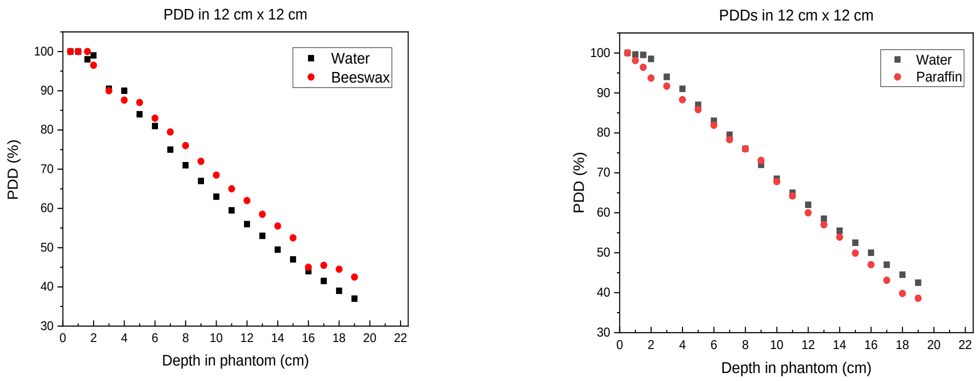
Figure 3: FLUKA simulated dose plot of 1.33 MeV primary beam interaction within beeswax for 12 cm × 12 cm.

Percentage depth dose curves

The values of percentage depth dose were calculated from dose/fluence obtained for various field sizes using Equation (1) (Praveenkumar 2013):

$$PDD(\%) = \frac{dose/fluence\ at\ a\ given\ depth}{dose/fluence\ at\ depth\ of\ maximum\ dose} \quad (1)$$

Comparative graphs for FLUKA simulated values for beeswax and paraffin were plotted each with PDD along *y-axis* and phantom depth along *x-axis* for the selected field size of simulation and compared with the data obtained from water. Water is used in this comparison because it is approved by IAEA as a standard material for calibration of radiotherapy machine as well as in dose determination in EBRT (IAEA 2000). For the sake of depth dose comparisons, plots of water, beeswax and paraffin were made. The PDDs obtained from these tissue equivalent materials for open field of 12 cm × 12 cm calculated using the FLUKA code are presented in Figure 4 (a) and 4 (b).

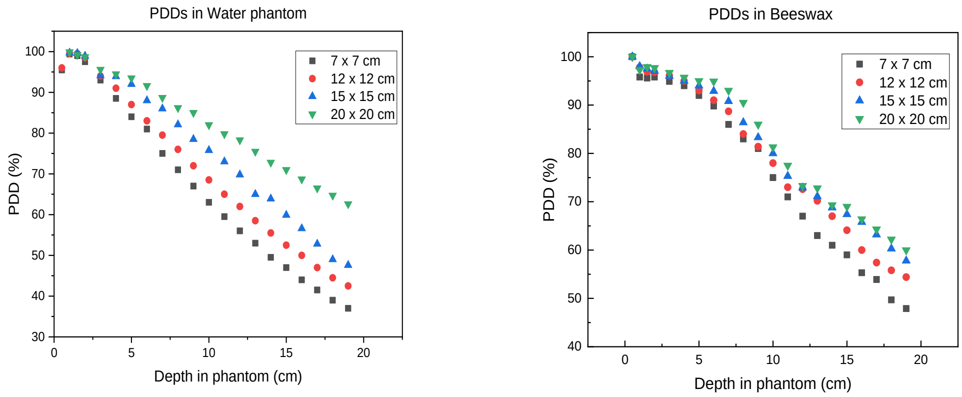


(a) (b)

Figure 4: The PDDs of selected tissue equivalent materials for open field size of 12 cm × 12 cm.

Figure 4(a) compares the relative central axis dose of water and beeswax, while that of Figure 4(b) compares dose of water and paraffin. Dose profile comparison for open field sizes of 12 cm × 12 cm presented in Figure 4 (a) shows that the water and beeswax dose data have good agreement with each other. However, there is a visible deviation of PDD between water and beeswax as well as between water and paraffin. The coefficients of variation of about 0.38% were obtained between water and beeswax (Figure 4 (a)), whereas for the case of water and paraffin, the deviation was minimal with less than 0.2% coefficients of variation for all data. The observed minor variations could be attributed to the geometry settings and different compound mixtures of materials used in this FLUKA simulation. It is worth to note that the PDD value for beeswax remain above that of water just after the depth of 3 cm. It is also noted that, the PDD in paraffin remain below the values of PDD in water just after the depth of 10 cm.

In order to further interpret the simulation results of photon dose produced by tele-cobalt machine, PDDs distributions of central-axis photon beam for various field sizes in water and beeswax were also calculated by FLUKA code. The results were compared for the four field sizes as presented in Figure 5(a) and 5(b).



(a) (b)

Figure 5: Central axis depth dose obtained from FLUKA MC Simulation for selected field sizes as a function of depth at 80 cm SAD.

The value of equivalent dose (*DOSE-EQ*) obtained from this simulation in beeswax phantom shows that there are of variations in photon doses (pSv/primary weight) which also cause the PDD at different points to vary with respect to depth and field size. It has been confirmed that beeswaxes represents an excellent option for a base tissue substitute in external beam radiotherapy with megavoltage photons (Vidal and Souza 2012). It is evident that the PDDs are strongly influenced by the field size (Figure 5 (b)). This explains why there are small coefficients of variation from 0.25% to 1.24% for field size of 7 cm × 7 cm and that of 20 cm × 20 cm, respectively.

Finally, the simulated data of PDD obtained from field size of 10 cm × 10 cm for beeswax and water phantoms were compared with British Journal of Radiology (BJR) supplement 25 (BJR 1996) data and presented in Figure 6. For a given depth in phantom, PDD decreases with increasing depth in phantom for photon beam of Co-60. The reason for this is the progressive reduction in scatter radiations with the increasing distance from the central axis.

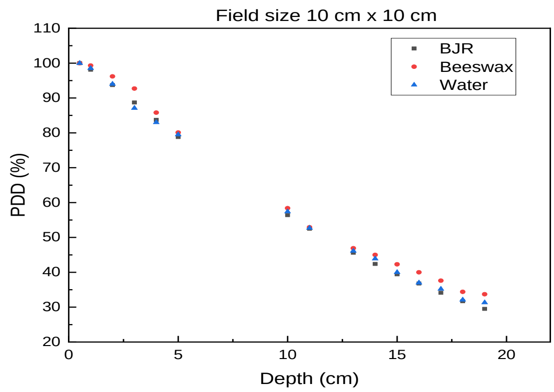


Figure 6: Comparison of central axis depth dose curve for beeswax and water in percentage calculated for 10 cm × 10 cm with measured data from BJR standard.

The PDD values for water and beeswax phantoms were in agreement with that of BJR data. The average coefficients of variation of about 0.98% were obtained between beeswax and BJR data, whereas for the case of water and BJR data, the average coefficient of variation was minimal with not more than 0.38% for all the data.

The results presented in this work imply that the use of depth dose and isodose curve of beeswax phantom in dose planning can be a good tissue equivalent substitute. However, there are large variations with PDD changes when increasing phantom depth. Therefore, dose planning for deep tumors need to be done with the maximum attentiveness; this is because the dose to the deep seated targets is visually lower than that of the other treatment plans (Sheikh et al. 2019). It is clear from our findings that, on Theratron Equinox 80 simulations, beeswax phantoms can be used for radiation dosimetry of photons in the energy range from 1.0 MeV to 2.0 MeV, as reported previously by Battistoni et al. (2016).

Conclusion

The analysis conducted in this study demonstrates that beeswax phantom has a potential to provide a better alternative to water phantom. Beeswax phantom can be used as substitute material for *in-vivo* dosimetry in EBRT using Theratron Equinox 80 Co-60 unit at Ocean Road Cancer Institute. However, further investigation on the validation of simulated data with the experimentally measured values using both water and beeswax phantoms are still needed to help radiotherapy based applications.

Conflict of interest

The authors declare no conflict of interests.

Acknowledgments

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