Clinical and Experimental Health Sciences

The Investigation of Tissue Composition Effects on Dose Distributions Using Monte Carlo Method in Permanent Prostate Brachytherapy

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ABSTRACT

Objective: Radiation dose calculations in the prostate brachytherapy practices have very high importance in terms of the success of treatment. The purpose of the present study is to determine whether there is a significant dose difference between the radiation dose calculations performed in water medium and prostate cancer-diagnosed patients by using the Monte Carlo method.

Methods: The radiation dose calculations were performed on 20 prostate patients by using the BrachyDose Monte Carlo code. Phantom geometry derived from real patients computed tomography (CT) data was created to use in dose calculations. Water material was assigned to all voxels within the prostate volume for dose comparison with CT derived phantom. ^{125}I (Amersham, OncoSeed, 6711), ^{103}Pd (Theragenics Co., TheraSeed, 200) and ^{131}Cs (IsoRay Medical) commercial brachytherapy seed models were used in dose calculations.

Results: It was observed that there are significant dose differences between the water medium and the prostate tissue. The differences between D90 dose values in prostate tissue and water medium were calculated as 7.2-10.5%, 9.1-13.4% and 5.4-8.3% for ^{125}I, ^{103}Pd and ^{131}Cs brachytherapy seed sources, respectively.

Conclusion: It was concluded that material compositions of different organs and tissues in the human body should be considered for more accurate brachytherapy dose calculations.

Keywords: Brachytherapy, prostate cancer, tissue composition, Monte Carlo, brachydose

1. INTRODUCTION

Low dose rate (LDR) permanent seed sources have been used frequently in the treatment of early-stage prostate cancer (1). In the dose results of brachytherapy seed sources used in the treatment of such cancers, the choice of appropriate dosimetry and dose calculation formalism is very important issue in terms of patient dose. Because the dominant interaction type is the photoelectric effect in brachytherapy seed sources such as ^{125}I, ^{103}Pd and ^{131}Cs, tissue heterogeneity-induced dose differences need to be considered in the treatment planning systems (TPS) for sensitive dose calculations (2,3). The ^{125}I, ^{103}Pd and ^{131}Cs brachytherapy seed sources are often preferred in permanent prostate cancer brachytherapy. However, high dose rate (HDR) ^{192}Ir radioactive sources are used especially in cervical and breast cancers.

The dose calculation formalism recommended by the Task Group No. 43 (TG-43) report of the American Association of Physicists in Medicine (AAPM) is used to obtain dose distributions in tissue or organs in current brachytherapy TPSs (4). One of the basic assumptions of this formalism is that the infinite and homogeneous water phantom can be used instead of tissue and organ materials. According to AAPM TG-43 report, the dose distributions are 2-dimensional, and this formalism is still used in determining the dosimetric characteristics of brachytherapy sources. So far, in the literature, there have been various studies carried out on water and tissue mediums related to low-energy brachytherapy seed sources (5,6). The dose values in some of these studies were calculated by using the dose calculation formalism recommended by the TG-43 report of AAPM.

Task Group No. 186 (TG-186) report of AAPM on model-based dose calculation algorithms (MBDCAs) has been recently published to calculate precise dose values in LDR brachytherapy dosimetry, which was developed as

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an alternative to the TG-43 formalism. In this report, photoelectric cross-sectional effect and scattering conditions for different mediums were analyzed with high precision in brachytherapy dose calculations (7). The TG-43 formalism is predominantly a good approximation method in high-energy photon interactions where Compton scattering occurs. It has been shown in studies that the dominant interaction type is the photoelectric effect and whole-body tissues cannot be accepted as water equivalent, when considering the photon energies (< 100keV) emitted from brachytherapy seed sources. It has been known that there are substantial dosimetric differences between the actual dose delivered to the patient and the dose values calculated using TG-43 formalism during treatment planning because the photoelectric cross-section is proportional to the effective Z value (8).

Unlike TG-43 formalism, MBDC algorithms can perform sensitive brachytherapy dose calculations with Monte Carlo-based simulations in a heterogeneous tissue based on real patient data. However, this approach is not yet used in LDR ^{125}I, ^{103}Pd and ^{131}Cs brachytherapy applications in TPS. Therefore, Monte Carlo simulations are needed to evaluate the dose differences between MBDCAs, and TG-43 based dose calculations. The MBDCAs using computed tomography (CT) data allow more precise dose calculations in different mediums such as inhomogeneous tissue and water since the data information about the mass density of each voxel and elemental composition of the mediums are available in the Monte Carlo method and other model-based dose calculation algorithms. Using the CT data in anatomical imaging and brachytherapy treatment planning can provide accurate density information for each voxel using the electron density of the tissue and the Hounsfield Unit (HU) calibration curves (9). Thus, the Monte Carlo simulation technique is proposed as an alternative to accurately transport low-energy photons emitted from seed sources in CT-based real patient geometry (10). Dose calculations in other studies were made on virtual phantoms and were prepared with the help of the information obtained from the CT data of real patients. The obtained results showed that the dose distributions in different tissue phantoms are different from the dose values obtained from the water phantom, and the elemental composition variations had a direct effect on the brachytherapy dosimetry. Therefore, it is still a matter of debate in the literature that the TG-43 formalism is preferable in brachytherapy dose calculations in the TPSs (11,12).

The aim of the present study is to determine whether there are significant dose differences between prostate tissue and water medium in LDR prostate brachytherapy using BrachyDose code Monte Carlo simulation.

2. METHODS

The radiation dose calculations in this study were performed by using the Monte Carlo technique, and the phantom geometry was obtained from CT images of patients diagnosed with 20 prostate cancer. The dose differences were calculated and compared between the prostate tissue and water medium for ^{125}I, ^{103}Pd and ^{131}Cs multiple brachytherapy seed sources. The phantom data were obtained from the CT images which are in the digital imaging and communications in medicine format (DICOM) and resized to be used in dose calculations effectively. Material information and mass density values of each organ and tissue were estimated by the reinterpretation of HU values at each point in the CT images. To do this, a calibration curve was used (13,14). In addition, HU numbers obtained only from patient data depend on the anatomical components of tissues and tissue density for each patient. Information about the medium material and XCOM cross-section values of different interaction types were obtained by the (Elektron Gama Shower national research center) EGSnrc data preparation program (15).

The brachytherapy seed source models used for dose calculations in this study are the LDR brachytherapy seed sources such as ^{125}I (Amersham, OncoSeed, 6711), ^{103}Pd (Theragenics Co., TheraSeed, 200) and ^{131}Cs (IsoRay Medical) (16–18). The Yegin's multi-geometry technique was used in the creation of the complex geometries of the brachytherapy seed source models used in the Monte Carlo particle transport calculations (19).

BrachyDose Monte Carlo code which is a model-based dose calculation algorithm was performed as a dose calculation tool. BrachyDose program uses a track length estimator calculating the kerma value by collecting the particle tracks in a certain volume to estimate the absorbed dose (20). $5x10^{10}$ photon histories were used during each simulation to reduce statistical error below 2.0%. Photon cut-off energy was taken as 1.0 keV in all dose calculations. Rayleigh scattering, photoelectric absorption, bound Compton scattering, and the characteristic X-rays released from K and L shells of related atoms were taken into consideration in Monte Carlo particle transport.

Phantom materials were defined as $D_{w,w}$ (TG-43) for the water phantom and $D_{m,m}$ (TG-186) for the prostate tissue. To perform Monte Carlo particle transport simulations, brachytherapy multi-seed sources were placed into the prostate tissue and homogeneous water phantom in all dose calculations. In addition, different scenarios were produced using a different seed source model each time. In each scenario, radiation dose distributions in the patient's body were calculated separately for ^{125}I, ^{103}Pd and ^{131}Cs brachytherapy multi-seed sources. In this study, dose calculations were performed using CT images of patients diagnosed with prostate cancer. To perform brachytherapy patient dose calculations, CT section images were resized to calculate patient dose more accurately. Therefore, voxel sizes of the phantom were reconstructed as $0.3x0.3x0.1cm^3$ cubic voxels in $91x91x27$ cm^3 cubic volume. Then, brachytherapy multi-seed sources were placed into the prostate volume in a 3-D grid of 1.0 cm spaced combination. During the simulation process, to minimize the dose that the urethra should be exposed to a minimum, particular attention was paid to the fact that the location of the seed sources in prostate tissue could not coincide with the

volume of the urethra. By choosing a convenient point in the prostate volume, where the dose gradient is minimized, the dose value at this point was normalized considering the dose distributions within the prostate volume. This study was conducted with approval from the Ethics Committee of the Necmettin Erbakan University, Faculty of Meram Medicine in Turkey (Approval number: 15/176).

ΔD (%), V_{100} and V_{150} clinical dosimetry parameters for prostate tissue and water medium, and dose homogeneity index (DHI) in prostate tissue volume were calculated through equations 2.1 and 2.2, respectively (21).

$$\Delta D(\%) = \frac{Dwater - Dprostate}{Dwater} \text{x}100 \qquad 2.1$$

$$DHI = \frac{V100 - V150}{V100} \qquad 2.2$$

Considering the TG-43 dose calculation formalism used in current TPS, the CT-based prostate patient phantoms were converted into a water equivalent homogeneous phantom. According to the idealized TG-43 formalism, $D_{w,w}$ (TG-43) dosimetric procedures in homogenous water phantom geometry were performed under the same conditions with CT-based prostate brachytherapy, and dose distributions were obtained from different multi-seed sources.

3. RESULTS

Figures 1-3 show the obtained isodose distributions using CT data of the prostate patient in a plane where multiple brachytherapy seed sources are sequenced. Dose to critical organs such as bone, bladder, and rectum, which were exposed to 125 Gy and higher dose for different seed sources, water and prostate tissue received in the same transverse plane is also illustrated in these figures. As a result of the calculations, it was observed that the differences in the dose distributions calculated at the same points in the prostate tissue and water medium for ^{103}Pd seed source were less when compared to ^{125}I and ^{131}Cs seed sources.

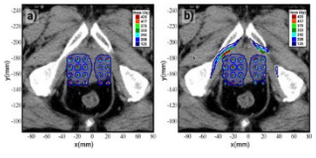

Figure 1. *Isodose curves for ^{125}I source. Monte Carlo dose calculations are carried out (a) in full $D_{w,w}$ water medium (b) in patient body which is made up of $D_{m,m}$ tissue materials.*

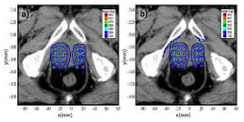

Figure 2. *Isodose curves for ^{103}Pd source. Monte Carlo dose calculations are carried out (a) in full $D_{w,w}$ water medium (b) in patient body which is made up of $D_{m,m}$ tissue materials.*

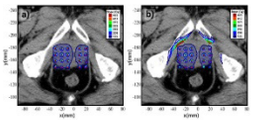

Figure 3. *Isodose curves for ^{131}Cs source. Monte Carlo dose calculations are carried out (a) in full $D_{w,w}$ water medium (b) in patient body which is made up of $D_{m,m}$ tissue materials.*

Dose differences were calculated and compared between the prostate tissue and water medium for ^{125}I, ^{103}Pd and ^{131}Cs multiple brachytherapy seed sources. Dose volume histograms (DVHs) with maximum dose differences between 20 patients are shown in Figures 4, 5 and 6, respectively. According to the results obtained from DVHs, it was observed that there are significant dose differences between the water medium and the prostate tissue. The minimum D_{90} values for prostate tissue and water medium were calculated as 7.2-10.5%, 9.1-13.4% and 5.4-8.3% for ^{125}I, ^{103}Pd, and ^{131}Cs multiple brachytherapy seed sources, respectively. Since the energy emitted from the ^{103}Pd brachytherapy seed source is about 30 keV, the photoelectric cross-section is dominant in this low dose range, and the D_{90} difference due to tissue composition mostly occurs from this seed source.

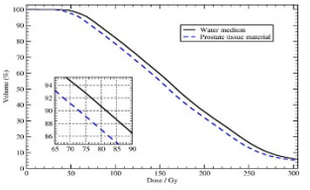

Figure 4. *Dose volume histogram obtained from the $D_{w,w}$ water medium and the $D_{m,m}$ prostate tissue for the Amersham OncoSeed 6711 125I brachytherapy seed source*

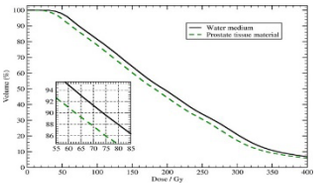

Figure 5. *Dose volume histogram obtained from the $D_{w,w}$ water medium and the $D_{m,m}$ prostate tissue for the Theragenics Co. TheraSeed 200 ^{103}Pd brachytherapy seed source*

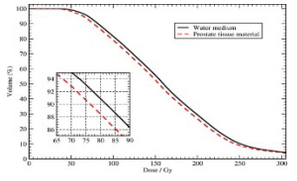

Figure 6. *Dose volume histogram obtained from the $D_{w,w}$ water medium and the $D_{m,m}$ prostate tissue for the IsoRay Medical ^{131}Cs brachytherapy seed source*

V_{100} and V_{150} values for prostate tissue were obtained on DVHs, and dose homogeneity index (DHI) was calculated

for different brachytherapy seed sources. DHI values were calculated as 0.28-0.54, 0.23-0.45 and 0.34-0.62 for ^{125}I, ^{103}Pd, and ^{131}Cs seed sources, respectively (Table 1). Since the DHI parameter is dependent on the V_{100} and V_{150} dosimetric parameters, this value is around 0.5 depending on the V_{150} / V_{100} ratio. However, it is ideally desired to be 1 in the treatment planning system.

Table 1. *Percentage dose differences between values of D_{90} calculated in prostate tissue and water medium for the ^{125}I, ^{103}Pd and ^{131}Cs brachytherapy seed sources*

Brachytherapy seed sources	Percentage (%) dose differences between D_{90} prostate tissue and D_{90} water medium	DHI
^{125}*I*	7.2-10.5%	0.28-0.54
^{103}*Pd*	9.1-13.4%	0.23-0.45
^{131}*Cs*	5.4-8.3%	0.44-0.62

D_{90}: *Dose covering 90% of volume; DHI: Dose Homogeneity Index*

In the dose calculations performed by sequencing the ^{125}I, ^{103}Pd, and ^{131}Cs multiple brachytherapy seed sources to the same coordinates of the prostate tissue and water phantom, significant dose differences were observed in transverse sections due to the difference of water phantom and prostate composition. Isodose distributions of water medium and prostate tissue in a slice are shown in Figure 7-9.

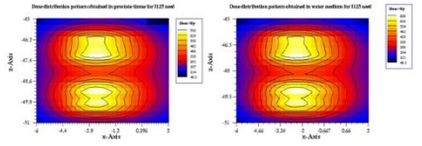

Figure 7. *Dose distribution pattern obtained in the same transverse section of prostate tissue and water medium for ^{125}I brachytherapy seed source*

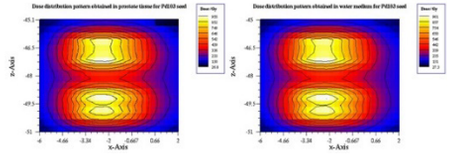

Figure 8. *Dose distribution pattern obtained in the same transverse section of prostate tissue and water medium for ^{103}Pd brachytherapy seed source*

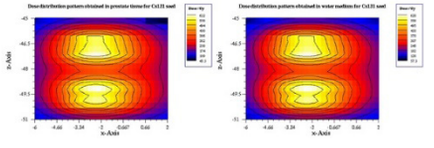

Figure 9. *Dose distribution pattern obtained in the same transverse section of prostate tissue and water medium for ^{131}Cs brachytherapy seed source*

4. DISCUSSION

When considering photon energies (< 100keV) released by brachytherapy seed sources, the dominant interaction type is the photoelectric effect. So, whether whole body tissues will be accepted as equivalent to the water is debated in the literature (22). The LDR seed sources are frequently used in permanent prostate brachytherapy. Especially in prostate brachytherapy due to the tissue composite, the photoelectric cross-section is dominant, so the dose distributions of LDR sources were examined in the study. In this study, the effect of phantom material compositions on the dose values calculated for prostate tissue and water medium was precisely investigated with a model-based dose calculation algorithm by considering TG-43 and TG-186 reports.

In prostate, breast and gynecology brachytherapy treatment planning systems, treatment planning is still carried out according to the AAPM TG-43 dose calculation formalism. However, some shortcomings in this formalism increase the need for using model based TG-186 dose calculation formalism in routine brachytherapy treatment planning systems. $D_{w,w}$ (TG-43) water medium and $D_{m,m}$ (TG-186) CT-based prostate tissue medium showed significant differences in 2-dimensional dose distribution patterns and minimum D_{90} values obtained from DVHs. Dose differences on the minimum D_{90} values for prostate tissue and water medium were calculated as 10.5%, 13.4% and 8.3% for ^{125}I, ^{103}Pd and ^{131}Cs multiple brachytherapy seed sources, respectively. These minimum D_{90} dosimetric values obtained from prostate tissue and water medium for different brachytherapy seed sources were found to be compatible with the literature (23,24). Until now, there have been various studies in the literature that were carried out on both $D_{w,w}$ water medium and $D_{m,m}$ prostate tissue regarding LDR multiple brachytherapy seed sources recommended in the reports of TG-43 and TG-186. In these studies, Chibani and Williamson calculated the difference between D_{100} dose values in prostate and water medium for ^{125}I and ^{103}Pd seed sources as 6% (25). Carrier et al. calculated the differences between water medium and prostate tissue as 4.4-4.8% for the D_{90} (26). Landry et al. calculated that D90 differences are up to 4% for prostate tissue and water medium. They also showed that dose distributions in prostate tissue differ from water and are influenced by density, mean tissue composition, and patient-to-patient composition variations (27). Landry et al. calculated as 8-9% the difference between D_{90} dose values in prostate and water medium for ^{125}I and ^{103}Pd brachytherapy seed sources (28).

In all these studies, when the dose distributions in the prostate tissue phantom were compared to the dose values obtained in virtual water phantoms such as TG-43, dosimetric differences due to composition variations occurred. In addition, the effect of dose differences induced tissue compositions has been demonstrated to be important in permanent implant prostate brachytherapy patient simulations by using multi-seed sources (29). The use of dose calculation algorithms such as Monte Carlo

in brachytherapy TPSs should be supported to obtain the sensitive dose values in tissue and water medium. The use of CT-based simulations, which contain detailed information about anatomical structures instead of water phantoms such as the idealized TG-43, can reduce dosimetric uncertainties in the brachytherapy treatment planning process due to tissue compositions. In addition, Monte Carlo model-based dose calculation algorithms can provide high dose accuracy in brachytherapy dosimetry.

A limitation of our study is that we only investigated the effect of the composition structure related to CT-based prostate tissue and water phantom on dose distributions using different LDR multiple brachytherapy sources. However, in further studies, it is necessary to consider not only the medium composition effect but also dosimetric parameters such as inter-seed effect and source positioning for multiple seed implant applications.

In addition, the dose homogeneity values depending on the V_{100} and V_{150} parameters for the ^{131}Cs brachytherapy source within the prostate target volume were better compared to ^{125}I and ^{103}Pd, and our results were found to be compatible with the literature (30).

We also observed that prostate brachytherapy isodose distributions have high dose values in bone tissue and its vicinity. Considering the dose distributions obtained in Fig. 1-3 for ^{125}I, ^{103}Pd and ^{131}Cs multi-seed sources, it was concluded that the dose distributions obtained by using the TG-43 formalism were inadequate in determining sensitive dose distributions especially in the vicinity of the bone region where heterogeneity was dominant. Based on the TG-43 and TG-186 recommendations, there are not enough studies in the literature regarding high radiation dose values that bone tissue may be exposed to in prostate brachytherapy (31,32), and this deficiency of literature can be investigated in further studies. Our results showed that TG-43 based dose calculations are quite insufficient for accurate dose estimation including tissue compositions. Therefore, it was concluded that MBDCAs in TPS can contribute to precise brachytherapy dose calculations by taking such effects into account. It was concluded that rearrangement of TG-43-based dose calculations to take organ and tissue materials into account or use of Monte Carlo-based dose calculation programs that take these effects into consideration in treatment planning systems is necessary for precise and accurate dose calculations.

Study limitations: In this study, the effects of tissue composition on dose distributions in the prostate medium were investigated. In future studies, it is necessary to examine the dose distribution in tissues such as the breast where tissue composition is dominant.

5. CONCLUSION

The dose simulation results calculated by the BrachyDose Monte Carlo code in this study make a significant contribution to the literature regarding the transition from TG-43 to MBDCA in clinical systems for sensitive dose calculations based on the effect of tissue composition. So, it was concluded that MBDCAs should certainly be considered for more accurate dose calculations in TPSs.

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