Effect of Tissue Composition on Dose Distribution in Electron Beam Radiotherapy

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ABSTRACT

Objective: The aim of this study is to evaluate the effect of tissue composition on dose distribution in electron beam radiotherapy.

Methods: A Siemens Primus linear accelerator and a phantom were simulated using MCNPX Monte Carlo code. In a homogeneous cylindrical phantom, six types of soft tissue and three types of tissue-equivalent materials were investigated. The tissues included muscle (skeletal), adipose tissue, blood (whole), breast tissue, soft tissue (9-components) and soft tissue (4-component). The tissue-equivalent materials were water, A-150 tissue-equivalent plastic and perspex. Electron dose relative to dose in 9-component soft tissue at various depths on the beam's central axis was determined for 8, 12, and 14 MeV electron energies.

Results: The results of relative electron dose in various materials relative to dose in 9-component soft tissue were reported for 8, 12 and 14 MeV electron beams as tabulated data. While differences were observed between dose distributions in various soft tissues and tissue-equivalent materials, which vary with the composition of material, electron energy and depth in phantom, they can be ignored due to the incorporated uncertainties in Monte Carlo calculations.

Conclusion: Based on the calculations performed, differences in dose distributions in various soft tissues and tissue-equivalent materials are not significant. However, due to the difference in composition of various materials, further research in this field with lower uncertainties is recommended.

Keywords

Electron Mode, Linear Accelerator, Monte Carlo Simulation, Soft Tissue, Tissue-equivalent Materials

Introduction

Since the early 1950s, high energy electrons have been used in radiotherapy. Application of megavoltage electrons, due to low penetration of electron beams in tissue and therefore reduced exposure of deep healthy tissues, is an appropriate method for treatment of superficial tumors. One of the features of electrons is rapid dose drop-off in the regions beyond the tumor [1].

International Commission on Radiation Units and Measurements (ICRU) has recommended in report No. 24 [2] that the uncertainty in dose delivery to the patient in radiotherapy should be within ±5%. To reach such a level of accuracy, all kinds of errors and uncertainties at

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various steps of treatment such as dose calculations, treatment planning and dose delivery should be minimized.

In electron beam dosimetry, total mass stopping power, $(S/\rho)_{tot}$, involves two mass stopping powers:

$$(S/\rho)_{tot} = (S/\rho)_{col} + (S/\rho)_{rad} \quad (1)$$

In this equation, $(S/\rho)_{col}$ refers to mass collision stopping power and $(S/\rho)_{rad}$ to mass radiation stopping power. Mass collision stopping power originates from the interaction of electron beam with orbital electrons (which results in excitation and ionization of atoms). On the other hand, mass radiation stopping power, involves the interaction of the electron beam with atomic nucleus (which results in production of bremsstrahlung radiation). $(S/\rho)_{col}$ has an important role in electron dosimetry, because under conditions that the radiative photons escape from the volume of interest and charged particle equilibrium exist, the absorbed dose in a material can be expressed as follows:

$$D_{med} = \Phi_{med} \left(\frac{S_{col}}{\rho} \right)_{med} \quad (2)$$

In which is the electron fluence. For electrons, energy transfer is due to soft and hard collisions and according to ICRU report No. 37 [3] mass collision stopping power is determined by:

$$\frac{S_{col}}{\rho} = \frac{4\pi N_A Z}{A} \frac{r_e^2 m_e c^2}{\beta^2} z^2 \left[\ln\left(\frac{2m_e v^2}{I} \right) - \ln(1-\beta^2) - \beta^2 - \frac{C}{Z} \right] \quad (3)$$

From the above equation, mass collision stopping power (and therefore the absorbed dose) depends on the atomic number of the material. Furthermore, there are terms in this equation involving the charged particle's energy in dose in a medium, especially at low energy range. Various tissues have different densities, chemical compositions and effective atomic numbers. In other words, there are various weight fractions of elements within different tissues. This would result in different dose distribution in different soft tissues. Additionally, preclinical dosimetry is performed in water or a tissue equivalent material in a radiotherapy department. Then, dosimetry data are applied to estimate the dose in tissues during treatment planning. It can be predicted that the obtained dose at dosimetry step differs from the actual dose in body due to the differences in the compositions of the tissue equivalent material and tissues themselves.

Simulation of a linear accelerator in electron mode has been studied by Bahreyni Toossi, et al. 8, 12, 14 MeV electrons from a Siemens Primus linac was simulated using MCNPX Monte Carlo code and the electron beams dosimetry parameters in different fields have been obtained for a water phantom. The obtained results from the simulations confirmed the measurement data in a water phantom. The simulation programs can be used to assess dose distribution in a phantom for complex situations in which a direct measurement would not be feasible [4].

There are studies on evaluation of dose distribution or percentage depth dose for the cases of heterogeneity in phantom, and homogeneous phantom [5-6]. Nedaie, et al. [5] have studied dose distribution of 8 and 15 MeV electrons produced by a linear accelerator in homogeneous and heterogeneous phantoms using MCNP-4C code. There was agreement between results of the simulations and results of the measurement in a homogeneous phantom. Generally, the result of the simulation for the heterogeneous phantom differed from the measurements by about 2%. Chow and Grigorov [6] investigated dose distortions in a water phantom due to the presence of small air holes at the central axis of electron beams. 6, 9 and 16 MeV electron beams of a linear accelerator were used and percentage depth dose was calculated by Monte Carlo simulation for different depths, thicknesses and widths of air cavities and confirmed by in-phantom measurements. Ignoring an air cavity with 1 cm thickness in the build-up region for a 6 MeV electron beam, caused an increase in deliv-

ered dose. Therefore, the effect of air cavity as an inhomogeneity in the phantom should be taken into account in calculations of dose distribution.

Dosimetric effects of trace elements in tissues for low energy photon sources used in brachytherapy had been studied for normal and cancer tissues using Monte Carlo calculations by White, et al. [7]. Their results showed that dose distributions vary in the presence of trace elements, depending on the atomic number and fraction of the elements in tissue. Trace elements have a noticeable effect on the dose distributions of low energy photon sources in brachytherapy. Ghorbani, et al. [8] have calculated dose distribution in several different tissues in brachytherapy with photon-emitting sources. Sources were simulated using MCNPX code in a spherical phantom. Dose in radial distances in adipose tissues, breast tissues, soft tissue (4-component), brain (grey/white matter), muscle (skeletal), lung tissue, blood (whole), soft tissue (9-component) and water was calculated. Doses for these materials, and various sources were compared with dose in soft tissue (9-component). It was concluded that ignoring the compositions of tissues would cause a significant error in dose delivery in some cases in brachytherapy using photon-emitting sources.

In a study by Aubry, et al. [9], an electron dose calculation algorithm (Eclipse) was validated using Monte Carlo simulation by EGSnrc code in a heterogeneous phantom. Results were compared to measurements by radiochromic film. Four inhomogeneous phantoms and 6-18 MeV electron beams were used. Dose calculations in heterogeneous phantoms with Eclipse agreed within 3/3% mm with measurements by radiochromic film.

There are studies on various tissue equivalent materials such as water and perspex in electron beam [5] and prostate tissue, adipose tissue, and mammary glands in the presence of trace elements and effects of these elements in dose distribution in brachytherapy [7, 10-14]. Furthermore, there are studies on electron beams and tissue-equivalent and heterogeneous phantoms [9]. While several studies have been performed in brachytherapy and concluded that dose distribution depends on the compositions of different soft tissues, to the best of our knowledge, there is not any investigation on dose distribution of electron beams for various tissues and materials. The analogy of electron dosimetry to low energy photon brachytherapy is difficult because they are completely different modalities and different physical phenomena are involved. Due to the differences in densities, compositions, collision stopping power of various tissues, execution of such a study on the effect of composition of various soft tissues on electron dose distribution is useful. The aim of this study is evaluation of effect of composition of various soft tissues and tissue equivalent materials on electron dose distribution in radiotherapy with electron mode of a medical linear accelerator.

Materials and Methods

Validation of Siemens Primus Linear Accelerator Simulation

In this study the validated Monte Carlo programs of the head of Siemens Primus linac installed at Reza Radiation Oncology Center (Mashhad, Iran) were used based on a previous study [4]. The program was run with 8, 12, and 14 MeV of electron beams. In the previous study on this linac, the criterion for validation of the simulations has been the agreement between the percent depth dose data from simulations and in-phantom measurements for 10 cm×10 cm, 15 cm×15 cm and 25 cm×25 cm applicators. Comparisons have been performed based on gamma index calculations. Gamma index values were less than 1.0 for most data points, indicating agreement between the two sets of data.

Evaluation of Dose in Various Soft Tissues and Tissue-Equivalent Materials

Soft tissues evaluated include: muscle (skeletal), adipose tissue, blood (whole), breast tissue, 9-component soft tissue and 4-component soft tissue. The tissue equivalent materials include: water, A-150 tissue equivalent plastic and perspex. Homogeneous phantom including each tissue/material was simulated using MCNPX Monte Carlo code (version 2.4.0) [15] in 8, 12, 14 MeV electron energies for 10 cm×10 cm applicator. Each tissue/material was evaluated separately. Electron dose at different depths ranging from 0.2 cm to 8 cm on the central axis of the beams was calculated. The phantom was in the form of a homogeneous cylinder with diameter of 30 cm and height of 30 cm. As it was aforementioned, the validated programs of the head of the Siemens Primus linac from a previous study were used for evaluation of the dose distribution in various materials. Mass densities and elemental weight compositions of the soft tissues and tissue equivalent materials are listed in Table 1. The data in this table were adopted from report No. 44 [16] of the International Commission on Radiation Units and Measurements. Mass collision stopping power ($MeVcm^2/g$) for the soft tissues and tissue equivalent materials used in this study are listed in Table 2. These data were extracted from the web page of National Institute of Standards and Technology (NIST) which includes stopping power, density effect parameters, range and radiation yield tables for electrons in various materials [17]. The corresponding data for breast tissue was not reported in the webpage of NIST, therefore is not listed in Table 2.

The Monte Carlo input programs were run and the obtained electron dose data for each material were divided by the electron dose in 9-component soft tissue as a reference. The final results were presented as a table of relative

Table 1: Mass Density and Chemical Composition of Soft Tissues and Tissue Equivalent Materials Used in this Study [16]

	Adipose tissue	Soft tissue (4-component)	Breast tissue	Muscle (skeletal)	Blood (whole)	Soft tissue (9-component)	Water	A-150	Perspex
Density (g/cm^3)	0.95	1.00	1.02	1.05	1.06	1.06	1.00	1.12	1.19
H	0.114000	0.101174	0.106000	0.102000	0.102000	0.102000	0.111898	0.101330	0.080538
C	0.598000	0.111000	0.332000	0.143000	0.110000	0.143000	-	0.775498	0.599848
N	0.007000	0.026000	0.030000	0.034000	0.033000	0.034000	-	0.035057	-
O	0.278000	0.761826	0.527000	0.710000	0.745000	0.708000	0.888102	0.052315	0.319614
F	-	-	-	-	-	-	-	0.017423	-
Na	0.001000	-	0.001000	0.001000	0.001000	0.002000	-	-	-
P	-	-	0.001000	0.002000	0.001000	0.003000	-	-	-
S	0.001000	-	0.002000	0.003000	0.002000	0.003000	-	-	-
Cl	0.001000	-	0.001000	0.001000	0.003000	0.002000	-	-	-
K	-	-	-	0.004000	0.002000	0.002000	-	-	-
Ca	-	-	-	-	-	-	-	0.018377	-
Fe	-	-	-	-	0.001000	0.001000	-	-	-

Table 2: Mass Collision Stopping Power ($MeVcm^2/g$) for Soft Tissues and Tissue Equivalent Materials Used in this Study [17]

Energy (MeV)	Adipose tissue	Soft tissue (4-component)	Muscle (skeletal)	Blood (whole)	Soft tissue (9-component)	Water	A-150	Perspex
8	1.972	1.925	1.921	1.922	1.932	1.943	1.926	1.883
12	2.017	1.971	1.967	1.968	1.978	1.989	1.971	1.928
14	2.035	1.988	1.984	1.985	1.996	2.006	1.987	1.945

electron doses at different tissues and distances. Based on our definition, relative electron dose in a material is the electron dose in a voxel in the soft tissue or tissue equivalent phantom divided by the electron dose in the same voxel in reference phantom (9-component soft tissue phantom). Therefore, relative electron dose is a unit-less quantity. In each program, 5×10^8 particles were scored and the maximum statistical uncertainty in Monte Carlo calculation for the tally cells was 2.36%. In this program, source to surface distance (SSD) was 100 cm. F6 tally and 10 keV cut-off were used to obtain the absorbed dose of electrons. Other than energy cut-off, no other variance reduction technique was used. Dimensions of each cylindrical cell were 2 mm height and 1 cm diameter. Maximum type A uncertainty in Monte Carlo calculations for 10 keV energy cut-off with 1.5×10^9 particle tracking was 1.37%. This value for 1 keV energy cut-off with 5×10^8 particle tracking was 2.52%.

Results

Obtained results of relative dose to muscle (skeletal), adipose tissue, blood (whole), breast tissue, soft tissue (9-component) and soft tissue (4-component), water, A-150 tissue-equivalent plastic and perspex for 8, 12, and 14 MeV electron energies are listed in Table 3. These data are related to different in-phantom depths ranging from 0.2 to 8 cm on the central axis of the electron beams. Relative electron dose in water relative to 9-component soft tissue for 10 keV energy cut-off with 1.5×10^9 particle tracking and 1 keV energy cut-off with 5×10^8 particle tracking are listed in Table 4.

Relative electron doses in water with respect to electron dose in 9-component soft tissue in 8, 12 and 14 MeV electron energies are illustrated in figure 1.

Discussion

In the present study, the effect of tissue composition on dose distribution in radiotherapy by electron modes of a medical linac was evaluated. To serve this purpose, dose distributions in various soft tissues and tissue equivalent materials were calculated at various depths for 8, 12, and 14 MeV electron energies. Based on the obtained results (Table 3), while differences are observed between dose distributions in various soft tissues and tissue equivalent materials, which vary with the composition of material, electron energy and depth in phantom, they can be ignored due to incorporated uncertainties in Monte Carlo calculations. When one considers formula (3), mass collision stopping power depends on the atomic number of the material. In this formula the Z/A term relates to the electron density, which changes slowly with Z. The mean excitation potential (I) is also related to Z, however, the logarithm reduces its influence. The

Table 3: Relative Dose of 8, 12, 14 MeV Electron Beams. Relative Dose Rate of Electron in the Presence of a Material is the Dose Rate of Electron in the Presence of the Material Divided by Dose Rate of Electron in the Presence of Soft Tissue (9-component)

		Adipose tissue	Soft tissue	Muscle (skeletal)	Blood (whole)	Soft tissue (9-component)	Water	A-150	Perspex
Depth (cm)	Energy (MeV)								
0.2	8	1.00	0.98	0.98	1.00	1.00	0.98	1.00	1.00
	12	0.97	0.98	0.98	1.00	1.00	1.00	0.98	0.9
	14	0.98	0.98	0.99	1.00	1.00	1.00	0.99	0.98
1.0	8	0.97	0.97	0.97	1.00	1.00	0.99	0.97	0.97
	12	0.98	0.99	0.99	1.00	1.01	1.00	0.98	0.98
	14	0.99	1.00	1.01	1.00	1.00	1.01	0.99	0.98
1.5	8	1.00	1.03	1.02	1.00	1.01	1.01	1.00	0.97
	12	0.99	0.99	0.99	0.99	0.99	1.00	0.99	0.97
	14	0.98	0.99	0.99	1.00	0.99	1.00	0.98	0.97
2.0	8	0.99	0.99	0.99	1.00	1.00	0.98	0.99	0.96
	12	0.99	0.99	1.00	1.00	0.99	1.01	0.98	0.99
	14	1.00	0.99	0.99	1.00	1.00	1.01	0.99	0.98
2.5	8	0.99	1.01	1.01	1.01	1.00	1.04	0.99	0.99
	12	0.99	1.00	1.00	0.99	1.00	1.03	0.99	0.97
	14	1.00	1.00	0.99	1.00	1.00	1.01	1.00	0.99
2.9	8	1.01	1.00	1.01	1.02	1.01	1.01	1.01	1.00
	12	1.02	1.00	1.01	0.99	1.00	1.03	0.99	0.98
	14	0.99	1.00	1.0	1.00	1.00	1.01	0.98	0.97
3.3	8	0.99	1.01	1.02	1.01	0.99	1.02	0.99	0.97
	12	1.01	1.01	1.01	1.01	0.99	1.01	0.99	0.97
	14	1.01	1.01	1.01	1.01	1.00	1.02	1.00	0.99
3.5	8	0.98	1.01	1.00	0.99	1.00	1.03	0.98	0.96
	12	0.98	0.98	0.97	0.99	0.99	1.00	0.98	0.96
	14	1.00	1.01	1.01	1.00	1.01	1.01	0.99	0.97
4.0	8	0.97	0.99	0.99	0.98	0.99	0.99	0.97	0.96
	12	1.03	1.03	1.02	1.01	1.00	1.04	0.98	0.98
	14	1.02	1.01	1.01	1.01	1.01	1.02	1.00	1.00
4.5	8	1.01	1.02	1.02	1.02	1.00	1.05	1.01	0.97
	12	1.02	1.02	1.02	1.01	1.00	1.02	1.00	0.98
	14	1.00	1.00	1.00	0.98	1.00	1.01	0.98	0.96
5.0	8	0.98	1.01	1.00	1.00	0.99	1.00	0.98	0.99
	12	0.99	0.99	0.98	1.01	0.99	1.00	0.96	0.95
	14	0.99	1.00	1.01	1.00	1.00	1.02	0.98	0.96

		Adipose tissue	Soft tissue	Muscle (skeletal)	Blood (whole)	Soft tissue (9-component)	Water	A-150	Perspex
5.5	8	0.99	0.98	0.96	1.00	1.00	1.02	0.96	0.96
	12	1.01	1.00	1.02	1.02	1.01	1.03	0.96	0.96
	14	0.99	0.99	1.01	1.00	1.00	1.01	0.97	0.97
6.0	8	1.02	1.01	1.03	1.02	1.01	1.03	1.00	1.00
	12	1.00	1.00	1.00	1.01	1.01	1.01	0.96	0.96
	14	1.02	1.01	1.00	1.00	1.00	1.01	0.96	0.96
6.5	8	1.01	1.03	1.06	1.02	1.00	1.07	1.01	0.98
	12	1.00	1.01	1.00	0.99	0.99	1.02	0.97	0.96
	14	1.02	1.00	1.00	1.00	0.99	1.02	0.97	0.96
7.0	8	1.01	1.05	1.06	1.02	1.03	1.05	1.01	1.00
	12	1.01	1.01	1.00	1.00	1.00	1.01	0.98	0.96
	14	1.03	1.02	1.01	1.00	1.01	1.02	0.99	0.97
8.0	8	1.01	1.00	1.00	1.01	1.01	1.00	1.02	0.97
	12	0.94	0.98	0.96	1.00	1.01	1.04	0.94	0.91
	14	1.00	1.00	1.02	1.01	1.01	1.01	0.97	0.94

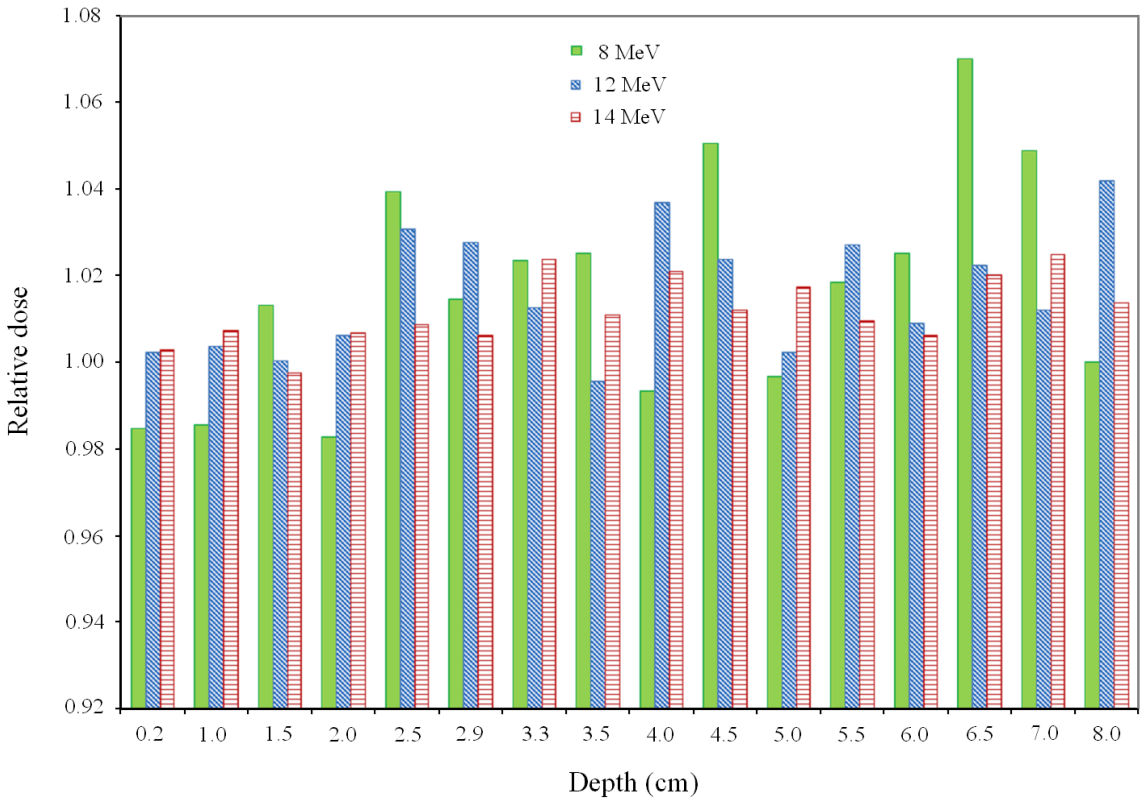

Figure 1: Relative Dose in Water with Respect to Soft Tissue (9-component) in 8, 12 and 14 MeV Electron Energies

Table 4: Relative Electron Dose in Water Relative to 9-component Soft Tissue for 8 MeV Electrons with 10 keV Energy Cut-Off and 1.5×10^9 Particle Tracking; and with 1 keV Energy Cut-Off and 5×10^8 Particle Tracking

Depth (cm)	10 keV cut off, 5×10^8 particles	10 keV cut off, 1.5×10^9 particles	1 keV cut off, 5×10^8 particles
0.2	0.98	0.99	1.01
1.0	0.99	1.00	0.99
1.5	1.01	1.02	1.01
2.0	0.98	1.01	0.97
2.5	1.04	1.02	1.01
2.9	1.01	1.00	1.03
3.3	1.02	1.01	1.04
3.5	1.03	1.02	0.99
4.0	0.99	1.00	0.98
4.5	1.05	1.02	1.03
5.0	1.00	1.00	1.02
5.5	1.02	1.01	1.04
6.0	1.03	1.00	0.99
6.5	1.07	1.06	1.04
7.0	1.05	1.04	0.99
8.0	1.00	1.01	1.03

polarity effect is also Z-dependent, but acts to reduce the stopping power. Taken together, for the relatively small range of densities and Z found in soft tissue, it is not surprising that there would be little effect. The data in this table does not indicate any special trend with electron energy and depth in phantom. Furthermore, the data presented in figure 1 for the relative electron dose in water relative to the dose in 9-component soft tissue for 8, 12 and 14 MeV electron energies does not prove a special trend for relative electron dose with electron beam's energy.

When one compares relative electron dose with 10 keV cut-off and 5×10^8 particle tracking with 10 keV cut-off and 1.5×10^9 particle tracking (Table 4), it seems that the data set with higher number of particle histories has less fluctuation. While this data set has a lower uncertainty (with maximum uncertainty of 1.37%), it does not indicate a significant difference between various tissues or tissue equivalent materials. A comparison between relative dose with 10 keV cut-off and 5.0×10^8 particle histories with 1 keV cut-off and 5.0×10^8 particle histories (Table 4) implies that there is not a meaningful difference between these two data sets. While both these data sets have the same levels of uncertainties (2.36% versus 2.52%), the program with 1 keV energy cut-off involves lower level of modeling approximation in dose calculation with Monte Carlo code. However, a meaningful difference between dose distributions in various materials with two data sets cannot be concluded.

Conclusion

Since mass density, chemical composition,

(Table 1) and mass collision stopping power (Table 2) of various soft tissues and tissue equivalent materials have differences, it is normally expected that electron dose distribution in these materials in radiotherapy with electron mode of a medical linac would be different. Treatment planning systems use the same compositions for various soft tissues in their calculations of dose distribution in radiotherapy. Dose delivery to patients is also based on the calculations of treatment planning systems. In addition, at the time of commissioning of a medical linac, water is used as a tissue equivalent material in radiation dosimetry. Then dose distribution in water is utilized in treatment planning system calculations to estimate dose distribution in human body. These calculations are based on some assumptions and approximations which are not theoretically true from a strict point of view. However, based on the calculations performed in the present study with various levels of uncertainties and energy cut-offs for various electron energies and materials, the differences in dose distributions in various soft tissues and tissue equivalent materials are not significant. It could be thought that having no differences in these cases may be due to the uncertainties involved in our calculations. Since ICRU [2] recommends that the uncertainty in dose delivery to the patient in radiotherapy should be within ±5%, having even low levels of errors in dose delivery could be important because these errors are summed. The total error in dose delivery has contributions from various factors such as: errors involved in in-phantom measurements, approximations in dose calculations in the treatment planning system, errors in patient positioning, etc. Therefore, further research in this field with lower levels of uncertainties and energy cut-offs is recommended. Furthermore, a similar study on other nominal electron energies would be also illuminating.

In the present study, a homogeneous phantom including a soft tissue or tissue equivalent material was defined in calculations. However, human body is not made up of a single, homogeneous soft tissue. It includes a variety of soft and hard tissues with different thicknesses. Definition of these geometric details and composition differences, similar to those encountered in a real situation in human body, and then having precise calculations on dose distribution in various tissues to estimate the involved errors in having the same compositions with treatment planning systems in electron beam radiotherapy could be as a subject of further investigations.

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Conflict of Interest

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