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Detailed analysis of dose difference in using water as tissue-equivalent material in ^{252}Cf brachytherapy

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ABSTRACT

Aim: The purpose of this study is to analyse how small variations in the elemental composition of soft tissue lead to differences in dose distributions from a ^{252}Cf brachytherapy source and to determine the error percentage in using water as a tissue-equivalent material.
Background: Water is normally used as a tissue-equivalent phantom material in radiotherapy dosimetry.
Materials and methods: Neutron energy spectra, neutron and gamma-ray dose rate distributions were calculated for a ^{252}Cf AT source located at the center of a spherical phantom filled with various types of tissue compositions: adipose, brain, muscle, International Commission on Radiation Units and Measurements (ICRU) report No. 44 9-component soft tissue and water, using Monte Carlo simulation.
Results: The obtained results showed differences between total dose rates in various tissues relative to water varying between zero and 4.94%. The contributions of neutron and total gamma ray doses to these differences are, on average, 81% and 19%, respectively. It was found that the dose differences between various soft tissues and water depend not only on the soft tissue composition, but also on the beam type emitted from the ^{252}Cf source and the distance from the source.
Conclusion: Assuming water as a tissue-equivalent material, although leads to overestimation of dose rate (except in the case of adipose tissue), is acceptable and suitable for use in ^{252}Cf brachytherapy treatment planning systems based on the recommendation by the ICRU that the uncertainties in dose delivery in radiotherapy should be lower than 5%.

1. Background

Californium-252 is an artificial element with a half-life of 2.645 years, which is used extensively in research, industry, and medicine.[1] It decays by both alpha emission (96.9%) and

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spontaneous fission (3.1%).[2] 3.1% of ^{252}Cf decays produces both neutrons and photons of varied energy. One microgram of ^{252}Cf emits 2.314×10^6 neutrons/s and 1.322×10^7 photons/s.[3] ^{252}Cf has the potential for both clinical brachytherapy and neutron capture therapy applications.[4] Due to its high neutron yield and relatively long half-life, in comparison to other spontaneous fission isotopes, ^{252}Cf is the best isotope choice for developing a neutron brachytherapy source.[3,5]

^{252}Cf was first suggested for clinical applications by Schlea and Stoddard,[6] and used as a brachytherapy source since the early 1970s. The neutrons emitted from the ^{252}Cf source interact with tissue through elastic scattering on nuclei, mainly hydrogen. The fast neutrons lose their energy by multiple scattering and are readily thermalized in vivo. The thermal neutrons are captured either by hydrogen or nitrogen available in human tissue.[7]

The uncertainty in absorbed dose required for local tumor control in radiotherapy was discussed by the International Commission on Radiation Units and Measurements (ICRU). ICRU in report No. 24 has recommended that the uncertainty in dose delivery in radiotherapy should be lower than 5%. To reach such a level of accuracy, all kinds of errors and uncertainties during the treatment process in radiotherapy should be minimized.[8,9]

In radiotherapy dosimetry, the same composition is usually considered for various soft tissues (like adipose, brain, muscle, etc.) and is in general represented by 9-component soft tissue or water liquid.[10,11] Since the cross-section of neutron and photon interactions with various types of tissue compositions is different, the absorbed dose rate in these materials will also be different. On the other hand, the Treatment Planning Systems (TPSs), the most valuable tools for estimation of dose to target volume and organ at risk in radiotherapy, routinely use the water medium for dose rate calculation.[12] Indeed, taking the same composition for various soft tissues and assuming water as a tissue-equivalent material, regardless of the effect of the composition of various soft tissues lead to an inaccurate estimation of dose rate distribution around the ^{252}Cf brachytherapy sources and can cause errors in dose calculations in ^{252}Cf brachytherapy treatment planning systems. Therefore, it is important to obtain the difference between dose rates in various soft tissues relative to 9-component soft tissue and water.

The neutrons and photons emitted from the ^{252}Cf source have varied energy and different linear transfer energy (LET) which interact with human tissue in different manners. Therefore, detailed calculation of the radiation components from the ^{252}Cf source in various types of tissue compositions is required to analyse the contribution of each individual dose component to the relative dose difference.

Aim

The purpose of this study is to analyse how small variations in the elemental composition of soft tissue lead to differences in dose distributions from a ^{252}Cf brachytherapy and to calculate the error percentage in using water as a tissue-equivalent material for a use assurance in the ^{252}Cf brachytherapy treatment planning systems.

Table 1 – Elemental composition and mass density of various soft tissues and tissue-equivalent materials (water).

Element	Adipose	Brain	Muscle	9-Component soft tissue	Water
Hydrogen	0.114	0.107	0.102	0.102	0.111898
Carbon	0.598	0.145	0.143	0.143	
Nitrogen	0.007	0.022	0.034	0.034	
Oxygen	0.278	0.712	0.710	0.708	0.888102
Sodium	0.001	0.002	0.001	0.002	
Phosphorus		0.004	0.002	0.003	
Sulfur	0.001	0.002	0.003	0.003	
Chlorine	0.001	0.003	0.001	0.002	
Potassium		0.003	0.004	0.003	
Density (g/cm^3)	0.95	1.04	1.05	1.06	0.998

2. Materials and methods

2.1. The simulated ^{252}Cf source geometry

In the present study, a ^{252}Cf applicator tube (AT) type source was modelled. The active portion of this source is a Pd:Cf_2O_3 cermet Matrix, which emits isotropic neutrons. It modelled as a cylindrical source cell with 12 g/cm^3 mass density, 15 mm length and radius of 0.615 mm. This active cylinder is doubly encapsulated comprised of Pt/Ir-10% mass. The primary capsule has inner and outer diameters of 1.35 and 1.75 mm, respectively, and inner and outer lengths of 15.50 and 17.78 mm, respectively. The inner and outer diameters of the secondary capsule are 1.80 and 2.80 mm, respectively, and the inner and outer lengths are 17.82 and 23.14 mm, respectively. The ends of the primary and secondary capsules were welded and rounded. Further, the 0.635 mm diameter Bodkin eyelet was also embedded in the secondary capsule of the source.[3] The geometry of the ^{252}Cf source simulated in this study is shown in Fig. 1.

2.2. Soft tissue composition

In this study, five types of tissue compositions: adipose, brain, muscle, International Commission on Radiation Units and Measurements (ICRU) report No. 44 9-component soft tissue and water were investigated. The ^{252}Cf source was positioned at the center of a 15 cm radius spherical phantom filled with each of these tissues. Each of these tissues was assumed as the phantom material in a separate simulation. The elemental composition and the mass density of these tissues adapted from the ICRU[11] are presented in Table 1.

2.3. Dose calculation

To illustrate the effect of tissue composition on dose distribution, the neutron energy spectra, and the neutron and gamma ray dose distributions from ^{252}Cf brachytherapy source were calculated in a phantom filled with various types of tissue compositions, through the Monte Carlo simulation. The total dose is the sum of dose contributions of neutrons, gamma rays emitted from the ^{252}Cf source and induced gamma rays resulted from the thermal neutron capture interactions. In

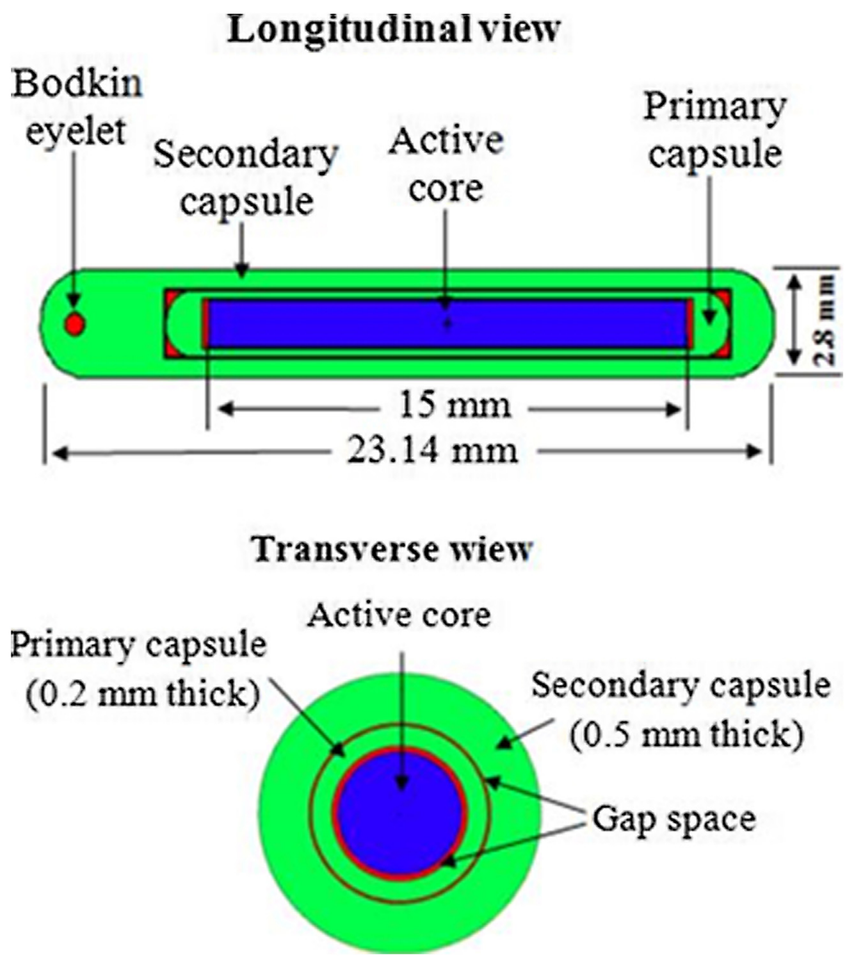

Fig. 1 – Geometry of the AT type ^{252}Cf source simulated in this study.

order to determine the error percentage in using water instead of soft tissue, the percentage dose difference between various soft tissues and water was calculated as follows:

$$\text{Percentage dose difference} = 100 \times \frac{\text{Total dose (various soft tissues)} - \text{Total dose (water)}}{\text{Total dose (water)}} \quad (1)$$

2.4. *Monte Carlo simulation*

In the present study, the MCNPX code (version 2.6.0)[13] was used to calculate dose rate distributions in various types of tissue compositions for the ^{252}Cf brachytherapy source. The F6 tally was used to calculate the neutron dose components, including fast, epithermal and thermal neutron doses. The energy deposited by both the source and induced gamma rays was obtained using the *F8 tally. The *F8 tally output (MeV) in each tally cell was divided by the mass of that cell to convert the energy deposited into dose (MeV/g). The source and induced gamma ray doses were calculated in a separate input file. The dose rate was determined in a cylindrical annulus of 0.2 cm thick × 0.2 cm deep, positioned at different distances along the transverse axis from the source center.

The neutron energy spectrum emitted from the ^{252}Cf was modelled as a Watt fission spectrum. The photon spectrum of the ^{252}Cf source was obtained from Stoddard and Hootman.[14] The thermal neutron region was defined to be below 0.5 eV, the epithermal neutron region from 0.5 eV to 10 keV and the fast neutron region over 10 keV. A number of 5×10^7 and 5×10^8 neutrons and photons, respectively, were run in each input file. Energy cut off for electrons and photons in all input files was set as 10 keV. The solid state S (α, β) neutron scattering library (lwtr.01 t) was used in order to improve the accuracy of low energy neutron transport calculations. The relative error of calculations was lower than 1%.

3. Results

To validate our Monte Carlo simulation, there is a comparison between the total dose rates in a water phantom calculated in this study by the experimental measurements of Colvett et al.[15] and the simulated calculations of Krishnaswamy in Fig. 2.[16] There is a good agreement between the values with small discrepancies, especially at distances close to the source. These discrepancies are attributed to the difference in

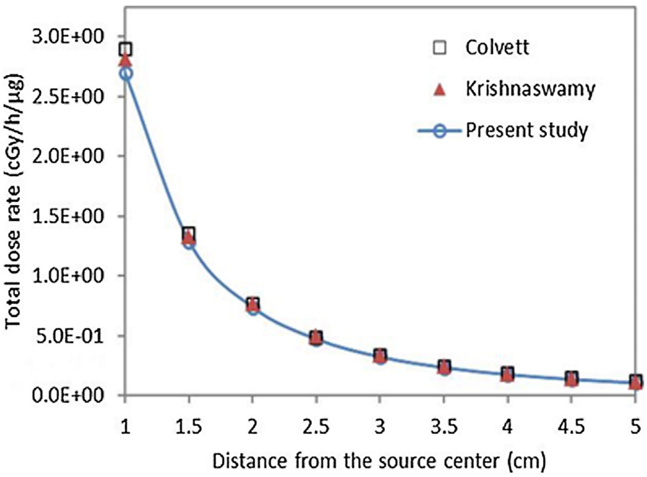

Fig. 2 – Calculated and measured total dose rates in the water phantom.

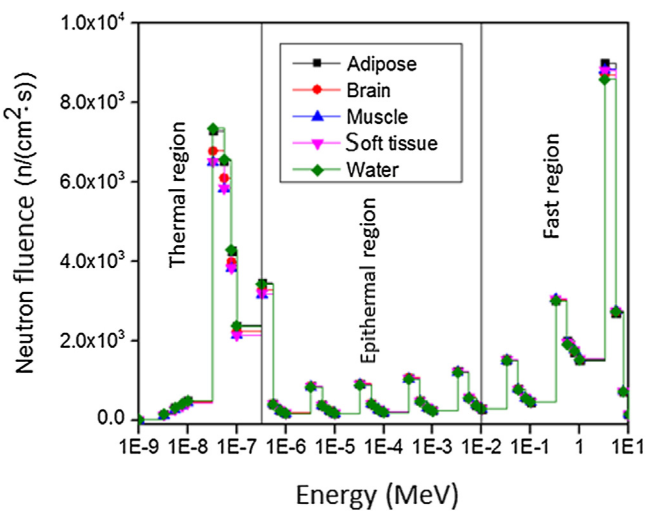

Fig. 3 – Calculated neutron energy spectra of the ^{252}Cf source, at a distance of 3 cm from the source center, in various types of tissue compositions.

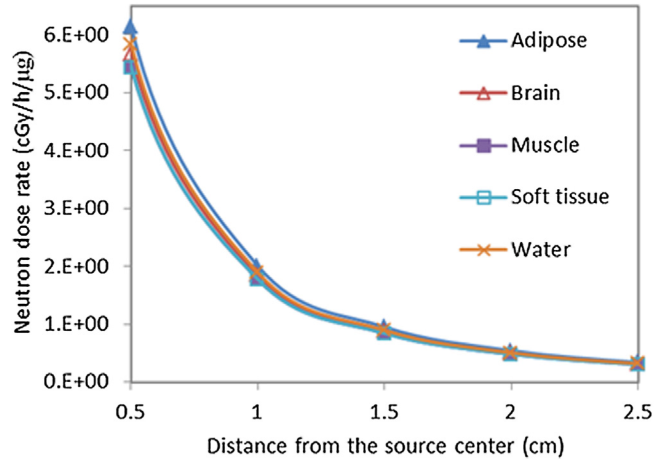

Fig. 4 – Neutron dose rate distributions at different distances from the source center in various types of tissue compositions.

the size of phantoms and in the modelled neutron and photon energy spectra of the ^{252}Cf source in the simulations or to the spatial precision and sensitivity of measurement devices to the rapid changes of dose rate.

After validation, the MCNPX code was applied for the calculation of ^{252}Cf neutron energy spectra and analyzing the neutron and gamma ray dose rate distributions in various types of tissue compositions. Fig. 3 shows the change of the ^{252}Cf neutron energy spectra calculated at a distance of 3 cm along the transverse axis from the source center in various types of tissue compositions. It is visible that the amounts of fast and thermal neutrons are increased and decreased, respectively, in various soft tissues in comparison to water. According to data in Table 1, this increment is attributed to the lower amount of hydrogen available in the brain, muscle and 9-component soft tissue and to the mass density difference of adipose relative to water.

Fig. 4 shows the neutron dose rate distributions at different distances from the source center in various types of tissue compositions. As can be seen, there is a small difference between neutron dose rates in various tissues. This difference, although small, is important in accurate estimation of dose rate distribution in ^{252}Cf brachytherapy.

Fig. 5a–c shows the neutron dose rate components at different distances from the source center in various tissues. In Fig. 5a, the fast neutron dose rate in various tissues decreases with increasing distance from the source as the inverse square of the distance. The difference between the fast neutron dose rates in various tissues is attributed to the difference in the amount of hydrogen in these tissues in scattering and moderation of fast neutrons. Among the studied tissues, the adipose tissue demonstrates the greatest values of the fast neutron dose rate at different distances from the source because of a larger abundance of hydrogen available in this tissue compared to the other studied tissues.

With decreasing the fast neutron energy, to the thermal energy range, the thermal neutron dose rate is increased and reaching its highest amount as can be seen in Fig. 5b. Afterwards, it is decreased due to the absorption of thermal neutrons by the hydrogen available in various tissues. The thermal neutrons mainly are captured either by hydrogen (0.33 b) in the $^{1}H(n, \gamma)^{2}H$ reaction or by nitrogen (1.83 b) in the $^{14}N(n, p)^{14}C$ reaction. The absorption of the thermal neutrons by nitrogen leads to increasing the thermal neutron dose rate. As follows from the data in Table 1, since the atom percentage of nitrogen available in various soft tissues is higher than water, the thermal neutron dose rate is more increased in various soft tissues compared to water.

Fig. 5c indicates that the values of epithermal neutron dose are significantly smaller than the values of fast neutron dose until the difference between epithermal neutron dose rates makes a noticeable difference between neutron dose rates in various tissues.

Fig. 6 displays the neutron dose rate as a function of energy at a distance of 3 cm from the source center. Obtained results show that the relative difference between neutron dose rates

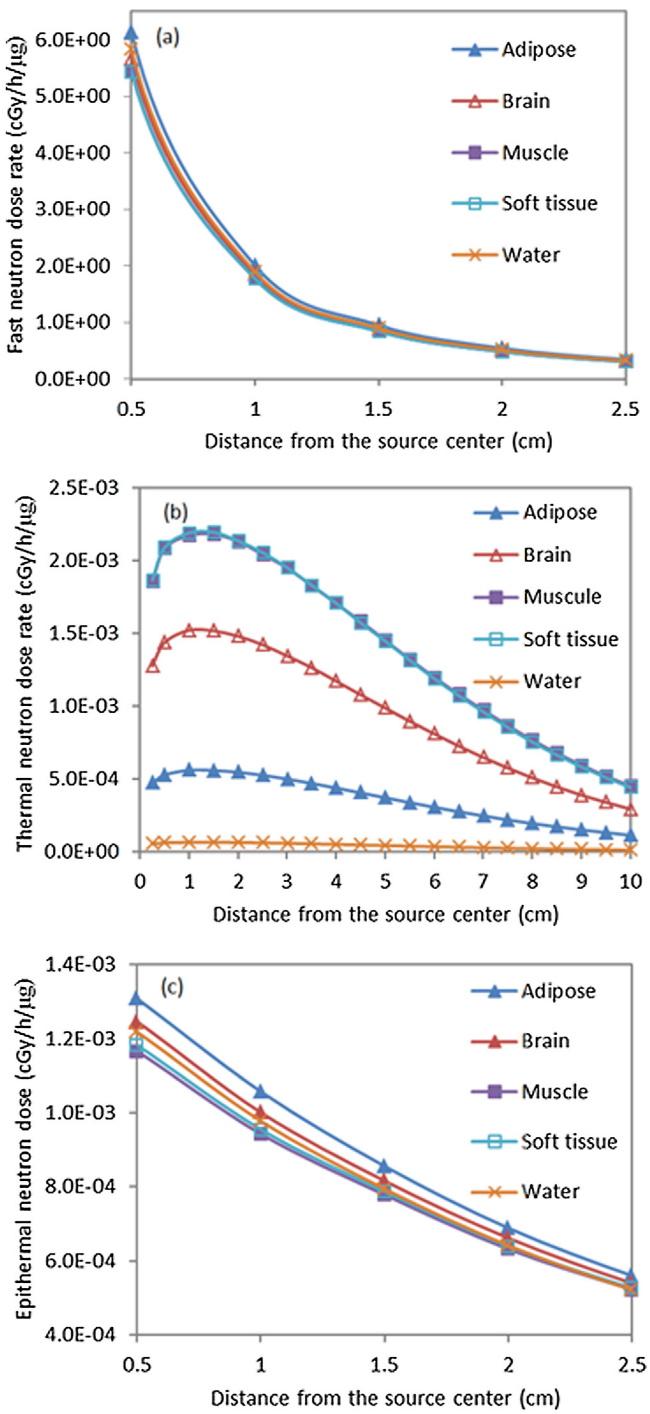

Fig. 5 – (a–c) Comparison between neutron dose rate components at different distances from the source center in various types of tissue compositions.

in various tissues is higher in the thermal and epithermal energy regions. Additionally, the values of the fast neutron dose are higher than those of thermal and epithermal neutron dose, which confirms the previous findings.

Fig. 7 shows the induced and source gamma ray dose rates at different distances from the source center in various tissues. As can be seen, the relative differences of induced and

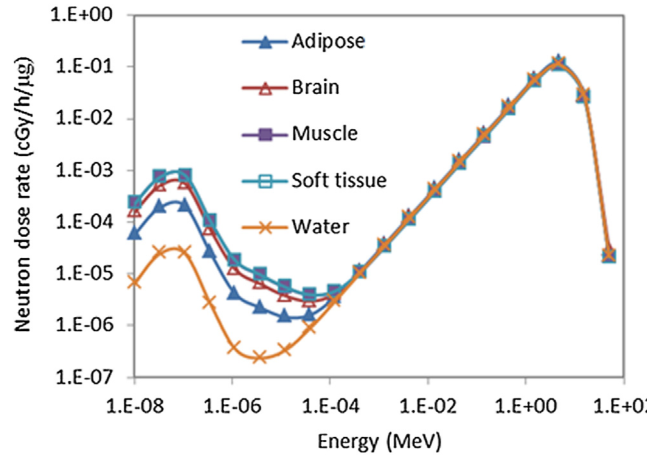

Fig. 6 – Neutron dose rate as a function of energy at a distance of 3 cm from the source center in various types of tissue compositions.

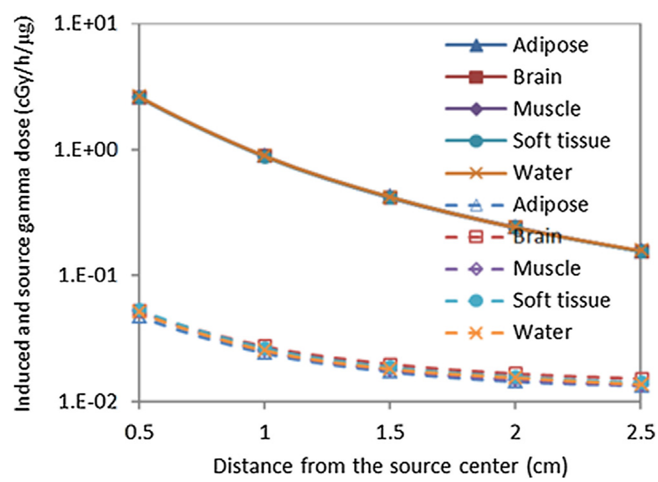

Fig. 7 – Induced and source gamma ray dose rates at different distances from the source center in various types of tissue compositions.

source gamma ray doses between various tissues are very small.

Table 2 contains the difference between total dose rates (neutron dose + total gamma ray dose) in various soft tissues relative to water at different distances from the source center. The data presented in Table 2 show that the total dose rates in all soft tissue, excluding the cases of the adipose tissue and the brain tissue at distances of more than 5 cm, are higher than those of water. Also, the total dose differences between various tissues and water vary between zero and 4.94% (corresponding to muscle tissue at a distance of 0.25 cm) that is lower than 5%.The data also show that the total dose differences are different at different distances from the source and generally decrease with distance from the source.

Fig. 8 shows the contributions of neutron dose and total gamma ray dose (source gamma ray dose + induced gamma ray dose) to the total dose differences between various soft tissues and water. This figure indicates that the contributions of neutron and total gamma doses to the dose differences

Table 2 – Percentage difference of total dose rates between various tissues and water.

Distance (cm)	Adipose	Brain	Muscle	9-Component soft tissue
0.25	3.379	−2.029	−4.938	−4.873
0.5	3.512	−2.112	−4.821	−4.740
1	3.956	−1.738	−4.534	−4.496
1.5	4.197	−1.726	−4.369	−4.235
2	4.594	−1.082	−3.796	−3.585
2.5	4.152	−1.288	−3.547	−3.677
3	4.467	−0.867	−2.981	−2.961
3.5	4.653	−0.580	−2.600	−2.552
4	4.585	−0.523	−2.758	−2.725
4.5	4.108	−0.367	−2.272	−2.275
5	4.285	−0.037	−1.698	−1.792
6	4.371	1.176	−1.205	−0.921
7	3.711	0.869	−1.262	−0.478
8	3.209	0.312	−1.479	−0.707
9	2.338	0.731	−1.055	−0.461
10	1.777	0.632	−1.564	−0.511

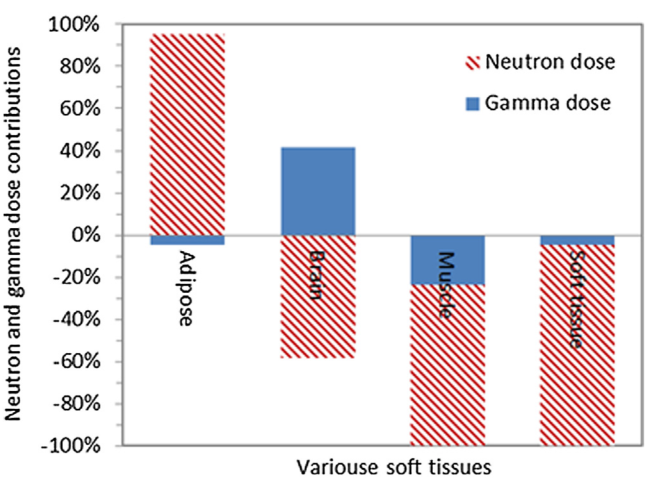

Fig. 8 – Contributions of neutron and total gamma ray doses to the total dose differences between various soft tissues and water.

are different for various soft tissues. The contribution of neutron dose to the dose differences for adipose, brain, muscle and 9-component soft tissue is 95.40%, 58.30%, 76.29% and 95.49%, respectively, while that of total gamma ray dose is 4.60%, 41.70%, 23.71% and 4.51%, respectively.

4. Discussion and conclusion

In this study, a detailed characterization of dose distributions in various types of tissue compositions: adipose, brain, muscle, International Commission on Radiation Units and Measurements (ICRU) report No. 44 9-component soft tissue and water was performed for the ^{252}Cf brachytherapy source, using the Monte Carlo simulation. Also, the error percentage in using water as a tissue-equivalent material for a use assurance in ^{252}Cf brachytherapy treatment planning systems was determined. A comparison between our Monte Carlo results and dosimetric data available in the literature is also presented to validate our simulation.

Khosroabadi et al.[17] have evaluated the effect of composition of different soft tissues and tissue equivalent materials on dose distribution in neutron brachytherapy with a ^{252}Cf source. MCNPX code was used and neutron/total dose rate was computed as absolute or relative dose for seven soft tissues and three tissue-equivalent materials. The effect of radial distance from the source was evaluated as well. Adipose and Plexiglass showed the greatest differences in total dose rate compared to 9-component soft tissue Furthermore, it was illustrated that the total dose rate in water differed from the total dose rate in 9-component soft tissue. It was concluded that the compositions of different soft tissues should be taken into account in dose calculation in neutron brachytherapy. It should be noted that there are differences between the methods of these two studies (the present study and the study by Khosroabadi et al.). In other words, in that study neutron and total dose rates in different soft tissues were compared with the neutron and total dose rates in 9-component soft tissue, but in the present study various neutron or photon dose components were evaluated compared to water. While the results cannot be compared reliably, referring to that study will upgrade the information on the difference in dose distributions in various soft tissue materials.

Obtained results showed that assuming water as a tissue-equivalent material leads to overestimation of dose rate (except in the case of adipose tissue) around the ^{252}Cf brachytherapy source and to dose differences. These dose differences vary for various types of soft tissue compositions (below 5%) and at different distances from the source. The contributions of neutron and total gamma ray doses to these dose differences are different for various soft tissues. It has mainly resulted from the difference in the amount of hydrogen available in these tissues since the contribution of neutron dose to these dose differences is dominant in comparison to the total gamma dose as can be seen in Fig. 8. Indeed, since the contribution of fast neutrons to the relative difference between neutron dose rates in various tissues is dominant, the difference in the amount of hydrogen available in these tissues in scattering and moderation of fast neutron is effective in these differences. It should be noted that the difference between the thermal and epithermal neutron dose rates in various tissues is larger than the fast neutron dose rates as can be seen in Fig. 5a–c, but since the values of thermal neutron dose are significantly smaller than those of fast neutron dose, the thermal and epithermal neutrons do not have a considerable contribution to the difference between the neutron dose rates in various tissues.

We found that the dose differences between various soft tissues and water for ^{252}Cf brachytherapy source depend not only on the tissue composition, but also on the beam type emitted from the ^{252}Cf source and the distance from the source. Since the uncertainties in dose delivery in radiotherapy should be lower than 5% as recommended by the International Commission on Radiation Units and Measurements (ICRU), assuming water as a tissue-equivalent material is acceptable and suitable for use in ^{252}Cf brachytherapy treatment planning systems.

Conflict of interest

None declared.

Financial disclosure

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