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Tissue composition effect on dose distribution in neutron brachytherapy/neutron capture therapy

Mohsen Khosroabadi[a], *Bagher Farhood*[b], *Mahdi Ghorbani*[c,*], *Nima Hamzian*[c,*], *Homa Rezaei Moghaddam*[a], *David Davenport*[d]

[a] *Faculty of Medicine, North Khorasan University of Medical Sciences, Bojnurd, Iran*
[b] *Department of Medical Physics and Biomedical Engineering, School of Medicine, Tehran University of Medical Sciences, Tehran, Iran*
[c] *Medical Physics Research Center, Mashhad University of Medical Sciences, Mashhad, Iran*
[d] *Comprehensive Cancer Centers of Nevada, Las Vegas, Nevada, USA*

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ABSTRACT

Aim: The aim of this study is to assess the effect of the compositions of various soft tissues and tissue-equivalent materials on dose distribution in neutron brachytherapy/neutron capture therapy.

Background: Neutron brachytherapy and neutron capture therapy are two common radiotherapy modalities.

Materials and methods: Dose distributions were calculated around a low dose rate ^{252}Cf source located in a spherical phantom with radius of 20.0 cm using the MCNPX code for seven soft tissues and three tissue-equivalent materials. Relative total dose rate, relative neutron dose rate, total dose rate, and neutron dose rate were calculated for each material. These values were determined at various radial distances ranging from 0.3 to 15.0 cm from the source.

Results: Among the soft tissues and tissue-equivalent materials studied, adipose tissue and plexiglass demonstrated the greatest differences for total dose rate compared to 9-component soft tissue. The difference in dose rate with respect to 9-component soft tissue varied with compositions of the materials and the radial distance from the source. Furthermore, the total dose rate in water was different from that in 9-component soft tissue.

Conclusion: Taking the same composition for various soft tissues and tissue-equivalent media can lead to error in treatment planning in neutron brachytherapy/neutron capture therapy. Since the International Commission on Radiation Units and Measurements (ICRU) recommends that the total dosimetric uncertainty in dose delivery in radiotherapy should be within ±5%, the compositions of various soft tissues and tissue-equivalent materials should be considered in dose calculation and treatment planning in neutron brachytherapy/neutron capture therapy.

* *Corresponding authors at*: Medical Physics Research Center, Mashhad University of Medical Sciences, Pardis-e-Daneshgah, Vakil Abad Blvd., Mashhad 9177948564, Iran. Tel.: +98 51 38002316; fax: +98 51 38002320.
E-mail addresses: mhdghorbani@gmail.com (M. Ghorbani), nh_mph84@yahoo.com (N. Hamzian).

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1. Background

Neutron brachytherapy is a type of high linear energy transfer (LET) radiotherapy which is effective in killing radioresistant cancer cells. This method has also been proven to be effective for treatment of intracavitary cancers of the cervix when it is used in combination with external beam radiotherapy. Californium-252 (^{252}Cf) is a neutron-emitting radionuclide recently applied in ^{252}Cf-based neutron brachytherapy in China.[1]

Boron neutron capture therapy (BNCT) is a noninvasive treatment which is an alternative for invasive treatment of malignant tumors. BNCT is used for treatment of a number of tumors such as glioma, melanoma, liver, cerebral metastasis, colon, sarcoma, head and neck, lung tissue and chest. This type of treatment consists of two steps: injection of a local medicine to the patient and irradiation of the patient with thermal neutrons. The cross-section of the neutron capture interaction with the injected drug is higher than that with other elements, such as hydrogen, nitrogen, and oxygen, which are present in tissue. When the patient is irradiated by thermal neutrons with energy of 0.025 eV, these neutrons interact with the capture agent (the injected drug) and this leads to biological damage to the tumor.[2]

^{10}B is a common isotope which is designed to be present in the injected drugs. This isotope is absorbed by tumor cells and consecutively the interaction of thermal neutrons with ^{10}B nuclei in tumor cells leads to production of ^{7}Li and α products which have a high linear energy transfer values (LETs). The resulting lithium ions and alpha particles carry the energy away.[3,4] The average energy in this case is 2.33 MeV.[5] Due to the limited ranges of the reaction products in tissue (5–9 μm), the destructive effects of the resulting projectiles are limited to cells containing ^{10}B.[6] Some other isotopes for use in neutron capture therapy (NCT) which have been introduced in recent studies are ^{157}Gd and ^{33}S.

Various neutron sources used in NCT consist of a reactor, an accelerator and a ^{252}Cf source. Recently ^{252}Cf has been used as a brachytherapy source for treatment of late stage cancers. Brachytherapy with a neutron source such as ^{252}Cf is more effective than brachytherapy with photon sources in treatment of tumors resistant to radiation, such as huge tumors, late stage tumors, melanomas, and glioblastomas.[5]

In the dosimetric formalism presented in the updated report by task group No. 43 (TG-43U1) of the American Association of Physicists in Medicine (AAPM), the dosimetric parameters are recommended to be calculated in a water phantom as tissue-equivalent media. Since the ^{252}Cf source which is used in neutron brachytherapy/neutron capture therapy is a neutron emitter, it is reasonable that the difference between neutron cross-sections in water and soft tissue would lead to differences between the absorbed doses in these two media. Since treatment planning systems (TPSs) calculations are routinely performed for water, ignorance of these differences in TPSs could lead to error in dose calculation and therefore dose delivery in neutron brachytherapy/neutron capture therapy.

There are some literatures which have focused on dose calculation in BNCT with ^{252}Cf source in various phantom media.[7–9] These studies investigated various media, such as muscle (skeletal), brain (grey/white matter), skin, blood (whole), pancreas, lung tissue, bone, A-150 plastic, plexiglass, human head phantom, and water. These studies demonstrated differences among the doses in various media. However, to the best of our knowledge, there is not a comprehensive study which evaluated a wide range of soft tissues and tissue-equivalent materials from various points of view. For example, in some studies (as an example in a study by Rivard[10]) the primary and secondary photon dose components were ignored in dose calculations and only neutron kerma rate was reported for various phantom materials. Since current calculations of TPSs are based on dose measurements in a water phantom, it is important to perform a quantitative study on various soft tissues and tissue-equivalent materials to calculate the differences between the doses in water and other soft tissues and media. The purpose of the current study is to assess the effect of the composition of various soft tissues and tissue-equivalent materials on dose distribution in neutron brachytherapy/neutron capture therapy.

2. Materials and methods

2.1. ^{252}Cf source geometry

In this study, an Applicator Tube (AT) model ^{252}Cf source, which has been constructed by Oak Ridge National Laboratory (ORNL),[11] was simulated using MCNPX (version 2.6.0) Monte Carlo code.[12] In the AT ^{252}Cf source, the cylindrical active core is Pd:Cf_2O_3 ceramic metal with a 1.5 cm length and a 0.615 mm radius. The source also has two capsules: primary and secondary. The primary capsule is composed of an alloy of 90% platinum and 10% iridium with an inner diameter of 1.35 mm and an outer diameter of 1.75 mm. The secondary capsule has the same composition as the primary one, but its dimensions differ from the primary capsule. In a previous study,[13] dosimetric parameters for the AT ^{252}Cf source were calculated and compared with those reported by the other studies. These parameters included air kerma strength conversion factor, dose rate constant, radial dose function, and total dose rate. Good agreement was observed between the data of ^{252}Cf source simulations in the previous study and the other reported data, therefore, the source simulations were approved. In the present study the verified simulations were used in evaluation of the effect of compositions of various media.

2.2. Soft tissues and tissue-equivalent materials

Seven soft tissues and three tissue-equivalent materials were used as the phantom material separately. The studied tissues were 4-component soft tissue, muscle (skeletal), brain (grey/white matter), adipose, blood (whole), lung tissue, and 9-component soft tissue. The tissue-equivalent materials were A-150 plastic, plexiglass, and water. The elemental compositions and mass densities of the materials were adopted from report No. 44 of the International Commission on Radiation Units and Measurements (ICRU).[14] For each element, various natural isotopes were also included in the calculations.[15]