THE THREE DIMENSIONAL MAP OF DOSE COMPONENTS IN A HEAD PHANTOM FOR BORON NEUTRON CAPTURE THERAPY

by

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The in-phantom measurement of physical dose distribution and construction of a convenient phantom is very important for boron neutron capture therapy planning validation. In this study we have simulated a head phantom, suggested for construction in boron neutron capture therapy facilities, and calculated all relevant dose components inside of it using the Monte Carlo code MCNPX. A "generic" epithermal neutron beam with a broad neutron spectrum, similar to beams used for neutron capture therapy clinical trials, was used. The calculated distributions of all relevant dose components in brain tissue equivalent were compared with those in water. The results show that water is a suitable dosimetry material and that the simulated head phantom is a suitable design for producing accurate three-dimensional maps of dose components at enough points inside of the phantom for boron neutron capture therapy dosimetry measurements and the use of these dose maps in beam development and benchmarking of computer-based treatment codes.

Key words: boron neutron capture therapy, head phantom, MCNPX code

INTRODUCTION

The interest in boron neutron capture therapy (BNCT) has experienced a significant revival in recent years. The BNCT therapy is expected to be very effective for several types of cancer such as malignant brain tumor and giloblastoma multiform (GBM), for which no successful treatment has been developed [1].

The physical concept of the method is based on a nuclear reaction that occurs when a nucleus of boron (^{10}B) captures thermal neutron, producing two high LET particles - an α-particle and a Li ion particle [2]. These heavy particles locally deposit their energy of 2.34 MeV in a range of 5-9 mm, which corresponds to the cell diameter. When a higher radiation dose is received by the tumor relative to adjacent normal tissue, that tumor cell will die [3].

During the exposure to neutrons, the absorbed dose in tissue is released by the various components of secondary radiations. Therefore, it is necessary to determine the absorbed dose and separate the various contributions due to each different secondary radiations produced by neutrons in tissue [1, 4]

The purpose of this paper is to simulate an appropriate head phantom for construction in BNCT treatment planning and calculate different dose components in many points inside of it where the measurement devices can be placed in experimental tests. The three dimensional maps of dose components were obtained in brain tissue phantom and compared to those in water as a suitable dosimetry material. All of the calculations were carried out using the Monte Carlo MCNPX code [5].

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MATERIAL AND METHODS

Phantom definition

The simulated model is an ellipsoidal acrylic walled anthropomorphic dosimetry phantom.

In order to insert detectors into the phantom volume, the phantom base is provided with 13 ports (the ports numbers are indicated in fig. 1) – one port on the phantom centre line and six ports, each one on the two concentric circles of 6 and 10.6 cm diameter. The ports are spaced 60° apart. The tubes with 1.30 cm outside diameter and 1.15 cm inside diameter can be inserted from these ports into the phantom volume. In this design, the point dose measurement devices, ion chambers, and gold foils can be held in position with an acrylic spacer at the end of the tubes (fig. 1). Our simulated model is so close to the brain model which is applied to NCT by Rogus *et all* [6].

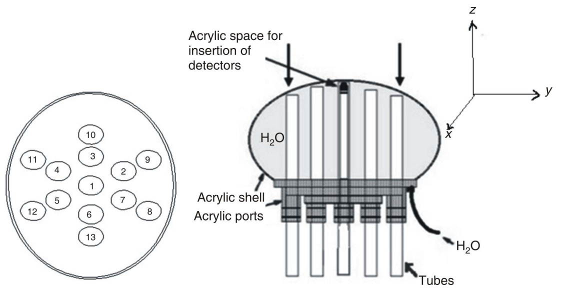

Figure 1. The bottom and side view of the simulated phantom

Neutron source

A generic epithermal neutron beam with 1% fast neutron flux contamination (10 keV to 2 MeV) and 10% thermal flux contamination (1 meV to 0.5 eV), similar to those proposed for use in clinical BNCT, was employed in this study. Inside each of the three energy bins of this epithermal spectrum, the modeled neutron spectrum approximated a 1/E distribution and all beams were 10 cm in diameter. The intensities of these beams were normalized to a neutron or photon flux of 10^{10} particle/cm^{2}s. For the generic epithermal neutron beam, the source biasing was used to sample the higher energy portion of the neutron spectrum more frequently and thereby reduce the statistical uncertainty of the fast neutron dose deep in the phantom [7]. The beam is monodirectional, and coaxial with z-axis of head phantom.

Dose computation

In BNCT the absorbed dose is from four contributors: the boron dose D_B; the therapeutic dose due to alpha and lithium particles released in the reaction of thermal neutrons with ^{10}B(n, α)^{7}Li , the nitrogen dose D_N (also called thermal neutron dose); the dose from protons due to the reaction of thermal neutrons with nitrogen ^{14}N(n, p)^{14}C , the gamma dose D_g; the dose from the reaction of thermal neutrons with hydrogen ^{1}H(n,)^{2}H and background, if not negligible), and the fast neutron dose D_{fn}; the dose mainly due to the recoil protons from elastic scattering with hydrogen nuclei ^{1}H(n, n')^{1}H. The different dose components, at each point of interest have their own "radiation quality", thus their own RBE. These dose components thus cannot be simply added. The biological effect of these dose components was widely studied and radiation type and boron compound weighting factors were determined in BNCT [4].

The total biologically weighted dose D_W is a sum of physical dose components (D_i) (*i. e.* absorbed dose) multiplied by weighting factors (w_i) of each dose component in a tissue. The weighted dose can thus be written as [1, 4]

$$D_w \quad w_g D_g \quad w_B D_B \quad w_N D_N \quad w_{fn} D_{fn} \qquad (1)$$

where D_g, D_B, D_N, and D_{fn} are physical dose of gamma, boron, nitrogen, and fast neutron, respectively. The weighting factors are w_g, w_B, w_N, and w_{fn} are 1, 1.3, 3.2, and 3.2, respectively The unit for absorbed dose (or physical dose) is gray, 1 Gy = 1 J/kg. As the weighting factors are dimensionless, gray is the unit of both the physical (D_g, D_B, D_N, and D_{fn}) and total biologically weighted dose (D_W). To illustrate the difference of the absorbed and weighted doses, the letter W in parenthesis is added to the symbol Gy writing one space between the symbol and the additional specification for the weighted dose, 1 Gy(W) [4]. The ^{10}B concentration of tissue was assumed to be 10 ppm (ppm = 10^{-6}). Elemental compositions of brain were taken from ICRU46 [8] .

The dose rate values were calculated in many locations of the phantom (along the longitudinal axis of each port). Neutron and gamma fluxes have been calculated by F4 tally. The corresponding dose values have been determined using flux to dose conversion factors (DE and DF cards). The neutron KERMA conversion for adult whole brain for H, C, N, O, and P is based on the kermas from ICRU63 [9].

RESULTS AND DISCUSSION

Dose distributions were calculated by placing a head phantom at 5 cm from exit of an epithermal neutron spectrum similar to the beams used for NCT clinical trials. All relevant dose components were determined in brain tissue equivalent phantom for the 10 ppm boron concentration . The results of brain were compared with water which is a brain equivalent material in dosimetry measurements. Since the irradiation is in z-direction, dose rate values were determined in many locations along the z-axis of all thirteen entries. The 3-D maps of total biologically weighted dose rates along the longitudinal axis of each port have been shown in figs. 2 and 3 for brain tissue and water, respectively.

The color bars on the right side of each figure indicate the value of dose corresponding to the color. It informs adequately of what is the dose rate value visually for each figure.

As the figs. 2 and 3 show, the part of phantom which is in the neutron beam path receives more doses. The dose rate values in port No. 1 (phantom centre line) are (more) higher than in other ports. This port is coaxial with neutron beam.

There are only minor differences between the dose rate in brain tissue and the water filled phantom, as the results show. It can be because of the hydrogen density of water and brain which differ by only a few percent. The results confirm that water is a suitable brain equivalent material in BNCT dosimetry measurements.

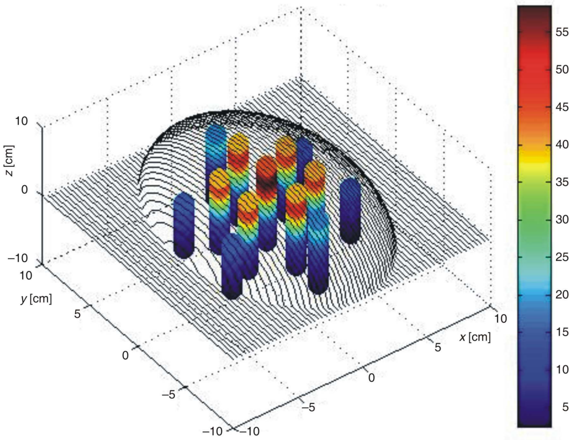

Figure 2. Total dose rate in the brain tissue filled phantom (RBE cGy/min)

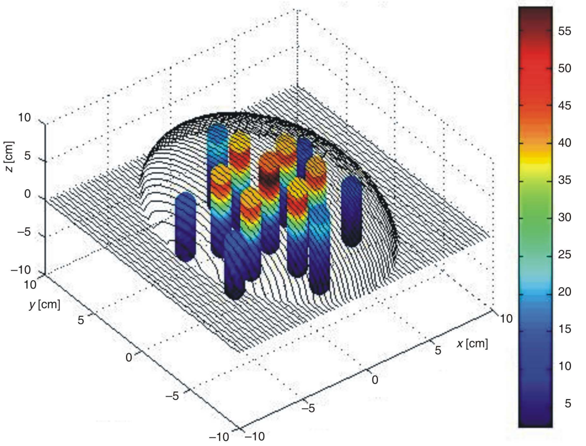

Figure 3. Total dose rate in water filled phantom (RBE cGy/min)

In order to show the difference of dose rates in brain tissue and water filled phantom clearly, dose rate values *vs*. depth of phantom were plotted for phantom center line (port No. 1).

As eq. (1) shows, total biologically weighted dose rate is sum of different physical dose rate components multiplied by their weighting factors. Different dose rates and total biologically weighted dose rate along the central axis of phantom (port No. 1) are presented in figs. 4-8.

Figure 4 indicates that gamma dose rate in brain is a bit (more) higher than water filled phantom. This is because of the absence of chlorine in water. The chlorine has a significant gamma cross-section and causes an increase in gamma dose rate of brain rather than water [10]. As we can see in fig. 4, gamma dose rate reaches a maximum at the depth of about 2 cm. It is due to the use of epithermal neutron beam as a source in our dosimetry calculations. With an increase of the depth in the phantom, the moderation of epithermal neutrons gives rise to thermal neutrons and thus increases gamma dose which is due to a reaction of thermal neutrons with hydrogen.

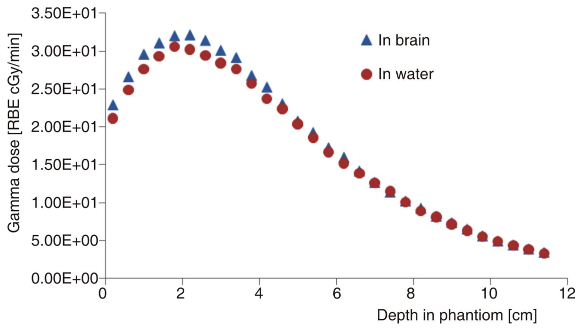

Figure 4. Gamma dose rate along the central axis of phantom (port No. 1)

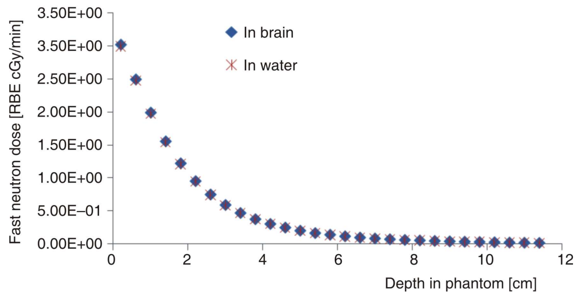

Figure 5. Fast neutron dose rate along the central axis of phantm (port No. 1)

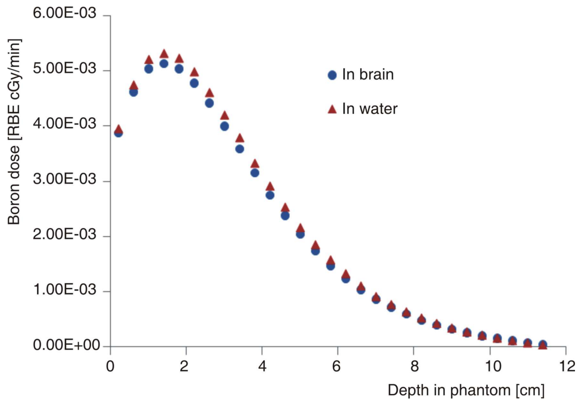

Figure 6. Boron dose along the central axis of phantom (port No. 1)

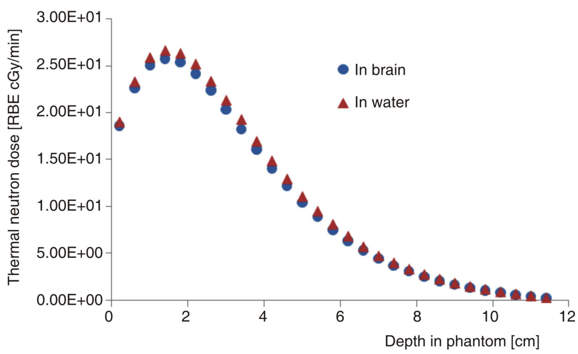

Figure 7. Thermal neutron dose rate along the central axis of phantom (port No. 1)

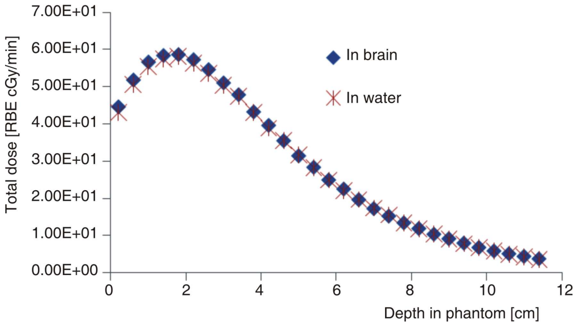

Figure 8. Total dose rate along the central axis of phantom (port No.1)

No significant differences are observed between the fast neutron dose rate in water and brain tissue, as fig. 5 shows. The fast neutron dose mainly is due to recoil protons from elastic scattering with hydrogen nuclei and since the hydrogen density of brain and water are close to each other, the fast neutron dose rate of brain is approximately same with the water.

We can also see that the fast neutron dose rate is attenuated faster with increasing depth in the phantom than with the other dose components.

The absence of nitrogen and chlorine in water increases the thermal neutron flux in water rather than brain and cause an increase in thermal neutron and boron dose. The boron dose is due to the reaction of thermal neutrons with ^{10}B. Thus, the increase of the thermal neutron flux increases the boron and thermal neutron dose rates in water rather than in brain tissue (figs. 6 and 7).

Total biologically weighted dose rate is defined as the sum of the above dose rates components, which have been indicated in fig. 8 for both brain tissue and water filled phantom. The total dose is almost identical in both cases.

CONCLUSIONS

In contrast to other forms of radiotherapy, the transport of neutrons is more sensitive to the shape and composition of the patient's body and involves a more complex assortment of radiation components having differing biological weighting factors which therefore need to be considered separately. The BNCT dosimetry technique is complex and one of the dosimetry requirements for clinical trials is employing an appropriate phantom. Because of these reasons we have utilized the Monte Carlo simulation to simulate a head phantom and calculate different dose component inside of it. It can be concluded that the simulated phantom is a suitable design for BNCT dosimetry measurements tests. It is close to the human head and the design permits the measurement of all relevant dose components at many locations within the phantom. Also the 3-D dose maps have been obtained. These dose maps permit provision of the data for comparison with computational treatment planning codes and beam development. The results also confirm water as a suitable dosimetry material.

AUTHOR CONTRIBUTIONS

This study was carried out by E. Bavarnegin under the supervision of A. Sadremomtaz and H. Khalafi. The manuscript was written by E. Bavarnegin and the figures were prepared by E. Bavarnegin with the help of supervisors and their ideas.

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ТРОДИМЕНЗИОНА МАПА КОМПОНЕНТИ ДОЗЕ У ФАНТОМУ ГЛАВЕ ЗА БОР-НЕУТРОНСКУ ТЕРАПИЈУ

Изградња погодног фантома и мерење расподеле дозе унутар њега веома су битни за планирање и потврђивање бор-неутронске терапије. У овом раду, према препорукама установа за бор-неутронску терапију и коришћењем MCNPX Монте Карло програмског пакета, симулиран је фантом главе и израчунате су све значајне компоненте дозе унутар њега. Коришћен је генерички епитермални сноп неутрона са широким спектром неутрона, сличан сноповима за клиничка испитивања бор-неутронске терапије. Израчунате расподеле свих значајних компоненти доза у еквиваленту ткива мозга упоређене су са расподелама у води. Резултати су показали да је вода погодан материјал за дозиметрију и да је симулирани фантом главе погодног дизајна за стварање тачних 3-D мапа компонената дозе у довољном броју тачака унутар фантома – употребљивих за дозиметријска мерења и тестирање програмских пакета за бор-неутронску терапију.

Кључне речи: бор-неутронска терапија, фантом главе, Монте Карло програм