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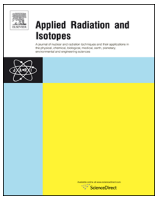

Optimum design of a moderator system based on dose calculation for an accelerator driven Boron Neutron Capture Therapy

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HIGHLIGHTS

- We performed design study based on RBE estimation for a BNCT moderator system driven by an accelerator.
- A moderator system consisting of MgF_2 combined with a Fe filter gives the best performance.
- The proposed model gives an epithermal neutron flux of more than $1.0 \times 10^9\ cm^{-2}\ s^{-1}$ and a dose ratio of 3.07.

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ABSTRACT

An accelerator based BNCT has been desired because of its therapeutic convenience. However, optimal design of a neutron moderator system is still one of the issues. Therefore, detailed studies on materials consisting of the moderator system are necessary to obtain the optimal condition. In this study, the epithermal neutron flux and the RBE dose have been calculated as the indicators to look for optimal materials for the filter and the moderator. As a result, it was found that a combination of MgF_2 moderator with Fe filter gave best performance, and the moderator system gave a dose ratio greater than 3 and an epithermal neutron flux over $1.0 \times 10^9\ cm^{-2}\ s^{-1}$.

1. Introduction

Boron neutron capture therapy (BNCT) is one of the useful methods of cancer therapy. So far neutron sources for BNCT are mainly reactors. A reactor is difficult to be constructed near a hospital and operated flexibly. Therefore, an accelerator driven neutron source which can be constructed easier than the reactor near a hospital has been desired. An accelerator based neutron source should be optimized more carefully than a reactor source since the neutron intensity produced is usually not so high and high energy component is larger than that of the reactor.

This study is an attempt to design a moderator system fulfilling medical treatment conditions for a proton accelerator based BNCT. Here, we assume a Be target and 8 MeV for a proton energy of the accelerator. The energy 8 MeV is based on the Tsukuba's accelerator-based BNCT research (Kobayashi et al., 2012) and is relatively small compared with energies so far used or planned for the Be target system, but we chose this energy since the lower energy will decrease activation and make maintenance easier. For optimization of the moderator system we study optimal materials and sizes to fulfill the condition of the epithermal neutron flux required for treatment with the maximized dose ratio of tumor to normal tissue.

2. Simulation methods

An accelerator conditions assumed are 8 MeV proton energy and 10 mA. Simulation geometry is illustrated in Fig. 1. It consists of a Be target, a filter, a moderator, a Pb reflector, a gamma shield of Bi, a collimator of B_4C resin and a phantom. Composition and weight percents of the phantom are as follows: 10.5 wt% for H, 25.6 wt% for C, 2.7 wt% for N, 60.2 wt% for O, 0.1 wt% for Na, 0.2 wt% for P, 0.3 wt% for S, 0.2 wt% for Cl, and 0.2 wt% for K (ICRU Report 44, 1989). A series of simulations have been carried out using the Monte Carlo code MCNPX (Pelowitz, 2008). Epithermal neutron flux was calculated at the outlet of the collimator without phantom. Energy range of epithermal neutron defined here is from 0.5 eV to 10 keV, thermal neutron less than 0.5 eV, and fast neutron more than 10 keV (IAEA-TECDOC-1223, 2001).

RBE dose is calculated using the following equation:

$$D_\alpha = CF_\alpha\, D_{B,\alpha} + RBE_n\, D_n + RBE_\gamma\, D_\gamma \qquad (1)$$

where the suffix α stands for tumor or normal tissue, D_α is the RBE

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dose and CF_α is the compound factor, which values are 3.8 for tumor and 1.3 for normal tissue. $RBE_{n\ \mathrm{or}\ \gamma}$ is relative biological effectiveness for neutrons and gamma rays and the values are 3.2 and 1.0, respectively. *CF* and RBE values were cited from the Brookhaven Medical Research Reactor (BMRR) protocol (Bleuel et al., 1998). $D_{B,n,\gamma}$ is absorbed dose for ^{10}B(n,α), neutron and gamma, respectively. Absorbed dose is calculated by an equation of a flux timed by the kerma factor.

The kerma factors for neutron and gamma were cited from DS02 (Kerr et al., 2003). $D_{n,\gamma}$ is given by

$$D_{n,\gamma} = \sum_i k_{\beta,i}\phi_{\beta,i}TI, \tag{2}$$

where the suffix i stands for energy group i, the suffix β stands for neutron or gamma ray, $k_{n,\gamma}$ is kerma factor for neutron and gamma, T is the irradiation time and I is the proton current. It should be noted that the DS02 neutron kerma coefficients for soft tissue are based on the four major elements of the body (hydrogen, carbon, nitrogen and oxygen) and applicable to neutrons whose energies range from 10^{-5} eV to 20 MeV.

The kerma coefficient for ^{10}B(n,α) is estimated by using the following approximate formula (Yonai et al., 2003).

$$k_B = 10^{[-0.496\times \log(E) - 16.815]}, \tag{3}$$

where k_B is the kerma coefficient and E (MeV) is the neutron energy. D_B is given by

$$D_B = \sum_i k_{B,i}\phi_{n,i}C_\alpha TI, \tag{4}$$

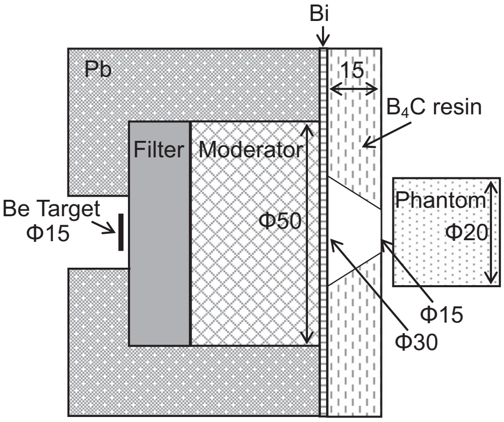

Fig. 1. Illustration of an assumed moderator system (unit: cm; Φ: diameter).

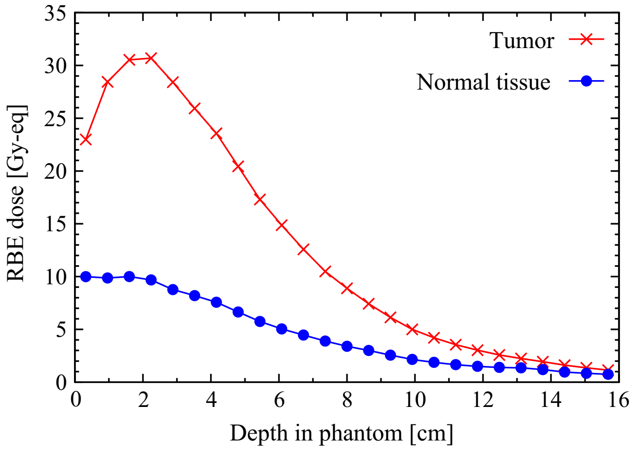

Fig. 2. Dose distributions for tumor and normal tissue (the RBE doses are normalized so that the maximum of RBE dose for normal tissue dose becomes 10 Gy eq).

where C_α is ^{10}B concentrations for tumor and normal tissues. ^{10}B concentrations of tumor and normal tissues were assumed to be 30 ppm and 10 ppm, respectively. Required value of the epithermal neutron flux at the outlet of the collimator is assumed to be more than $1.0\times10^9\ \mathrm{cm}^2\ \mathrm{s}^{-1}$ and dose ratio more than 3. The value of the epithermal neutron flux is the recommended value by IAEA-TECDOC-1223.The dose ratio is defined as a ratio of the maximum tumor dose to the maximum normal tissue dose.

Table 1
Filter thicknesses satisfying the criterion of epithermal neutron flux at the maximum dose ratio. The moderator is MgF$_2$ and the thickness is unchanged.

Filter	Thickness [cm]	Dose ratio
Fe	15	2.92
Al	16	2.35

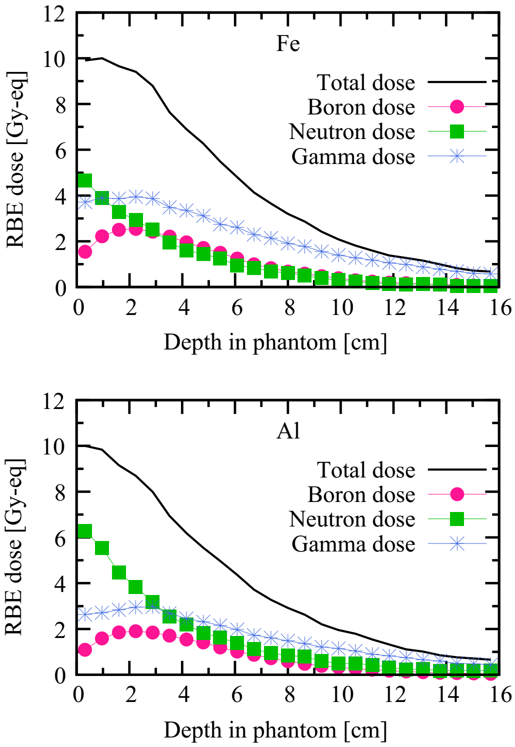

Fig. 3. Dose distributions for normal tissue (the RBE doses are normalized so that the maximum of RBE dose becomes 10 Gy eq).

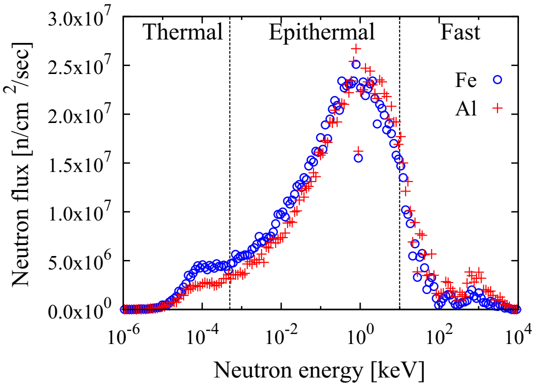

Fig. 4. Neutron spectra at the outlet of the collimator for Fe and Al filter cases.