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Verification of nuclear data for the Tsukuba plan, a newly developed treatment planning system for boron neutron capture therapy

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HIGHLIGHTS

- JENDL-4.0 is applied as nuclear data for a newly developed treatment planning system.
- The nitrogen dose according to JENDL-4.0 is different from END/F-B-VII.
- The distribution values determined with JENDL-4.0 agree the ENDF/B-VII calculations.
- Calculations with JENDL-4.0 can be applied to the BNCT dose calculation.

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ABSTRACT

Various verifications were performed to apply JENDL-4.0 as nuclear data for a newly developed treatment planning system with a homogeneous or precise human-like phantom. The nitrogen dose calculated by JENDL-4.0 differed slightly from that calculated by ENDF/B-VII.0. However, the total weighted dose-based dose volume histogram in the boron neutron capture therapy (BNCT) treatment for brain tumors calculated by JENDL-4.0 was in good agreement with the results of the ENDF/B-VII.0 calculation. Therefore, calculation with JENDL-4.0 can be applied to the BNCT dose calculation.

1. Introduction

Boron neutron capture therapy (BNCT) has been performed by using a neutron beam generated from a reactor. Currently, several studies on accelerator-based neutron sources for BNCT are being carried out in various countries (Kreiner et al., 2014; Green, 1998). In particular, in Japan, some commercial-based BNCT devices with accelerators are being developed. At Kyoto University, clinical trials using a cyclotron-based epithermal neutron source (C-BENS) are already being performed (Tanaka et al., 2011). In addition, a team including members from the University of Tsukuba is now developing a linac-based BNCT device (Kumada et al., 2014). To perform BNCT as a type of radiation therapy, a treatment planning system that can determine a suitable irradiation condition is needed. Thus, the University of Tsukuba is also developing a new treatment planning system (tentative name: Tsukuba plan) in addition to the linac-based BNCT device. The Tsukuba plan now involves the development of the entire system (considering the dose calculation code and nuclear data) to ultimately realize Japanese-made equipment by using several technologies and know-how accumulated from the development of JAEA Computational Dosimetry System (JCDS), which is a treatment planning system for BNCT applied to actual clinical trials conducted in JRR-4 (Kumada et al., 2007). A prototype of the Tsukuba plan has been completed. To apply the Tsukuba Plan to actual BNCT, we are currently conducting several verifications.

Regarding the dose-calculation algorithm installed in treatment planning system for BNCT, Monte Carlo method is usually employed in order to determine accuracy dose (Kumada et al., 2004; Zamenhof et al., 1996; Nigg et al., 1999). The Tsukuba plan has also adopted the Monte Carlo method. In the development of

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the Tsukuba plan, a new Monte Carlo transport code specific to radiotherapy has been developed on the basis of the Particle and Heavy Ion Transport code System (PHITS) (Sato et al., 2013). Moreover, JENDL-4.0, as the Japanese Nuclear Data Library (Shibata et al., 2011) is planned to be used as nuclear data for Monte Carlo transport calculation.

In this research, some verifications relevant to nuclear data were performed for the practical application of the Tsukuba plan. We verified the applicability of JENDL-4.0. As for the BNCT radiotherapy planning systems such as JCDS and NCTPlan (Zamenhof et al., 1996) put into practical use until now, ENDF/B (Chadwick et al., 2006) is used as nuclear data. On this basis, we performed irradiation simulations with two phantom models and calculated neutron fluxes and each dose component when using JENDL-4.0 or ENDF/B-VII.0. Further, the calculation results obtained from each nuclear data were compared.

2. Materials and methods

2.1. Dose components for the Tsukuba plan dosimetry

In dose estimation with JCDS developed for reactor-based BNCT, JCDS calculates the absorbed doses generated from the reactions between neutrons and boron-10 (boron dose), nitrogen (nitrogen dose), and hydrogen (hydrogen dose). Boron dose provides a therapeutic effect, and nitrogen dose and hydrogen dose have a large contribution to the dose in the composing elements of a human body. Furthermore, the primary gamma rays from the neutron source and the secondary gamma rays generated by the reaction with neutrons in a living body are also calculated. The soft tissue in the human body consists of not only nitrogen and hydrogen but also carbon, oxygen, etc., as shown in Table 1 (ICRU REPORT 44, 1989). Moreover, mass fractions for carbon and oxygen are significantly greater than those of hydrogen and nitrogen. In dose estimation with JCDS, to perform Monte Carlo transport calculation in a short time, absorbed doses from carbon (carbon dose) and oxygen (oxygen dose) have not calculated, because the contribution of the both doses to total weighted dose was not large. On the other hand, the Tsukuba plan which can compute many dose components at high speed with improved calculation method, estimates the carbon dose and the oxygen dose in addition to the conventional four dose components in order to determine total weighted dose more accurately than JCDS dosimetry.

In the verifications for nuclear data with the Tsukuba plan described below, the total weighted dose was determined based on the six dose components. The dose elements and their major reactions with neutrons are shown in Table 2.

Table 1
Major elemental composition for some materials applied to dose estimation with the Tsukuba plan.

	Elemental composition (% by mass)				
	Hydrogen	Carbon	Nitrogen	Oxygen	Calcium
Soft tissue[a]	10.5	25.6	2.7	60.2	
Bone[b]	5.0	21.2	4.0	43.5	17.6

[a] Elemental composition of soft tissue was referred from average soft tissue for adult male in ICRU report 44.
[b] Elemental composition of bone was referred from skeleton–cranium for adult in ICRU report 46.

Table 2
Main reactions for each dose components in BNCT.

Dose component	Reactions
Boron dose	α particle and ^{7}Li (^{10}B(n,α)^{7}Li)
Hydrogen dose	Recoiled proton (elastic scattering) ^{2}H (^{1}H(n,γ)^{2}H)
Nitrogen dose	Elastic scattering proton and ^{14}C (^{14}N(n,p)^{14}C)
Carbon dose	Elastic scattering
Oxygen dose	Elastic scattering
Gamma dose	Leakage component γ ray (^{1}H(n,γ)^{2}H)

2.2. Verification with a cubic phantom model

First, the applicability of JENDL-4.0 to the dose estimation for BNCT was verified by comparison with the dose calculations with ENDF/B-VII.0. An irradiation simulation of BNCT for a cubic $20 \times 20 \times 20$ cm^3 phantom model was performed (Fig. 1(a)). The material of the phantom was defined as soft tissue based on ICRU-44 (ICRU REPORT 44, 1989). Each elemental composition is shown in Table 1. We also assumed that 20 (μg/g) of boron-10 was uniformly distributed within the phantom. Irradiation of the phantom by the epithermal neutron beam of Japan Research Reactor No.4 (JRR-4) was simulated. We performed a dose evaluation using PHITS as the Monte Carlo code and the application of JENDL-4.0 or ENDF/B-VII.0 as nuclear data. Regarding evaluation for neutron flux distribution within the phantom, we obtained the neutron flux by using "T-Track" tally function which calculate track length of particles pass through any specified region (Niita, et al., 2015). Distributions for total weighted dose and for each dose component were also evaluated. Regarding the dose estimation, we were employed "heating number" built in nuclear data as kerma factor necessary for absorbed dose calculation. And each absorbed dose was determined for each tally region by using "multiplier" option in the T-Track tally function which can multiply automatically the heating number depending on energies of particle by the flux values based on the track length evaluation.

2.3. Verification with a realistic human head model

Next, a detailed realistic human head model, constructed with bone, soft tissue, air, and their combinations, was created by using computed tomography (CT) images of a head phantom (PB-1, Kyoto Kagaku Co., Ltd.) to validate the applicability of JENDL-4.0 to actual treatment planning. Each elemental composition applied to bone and soft tissue of the model is shown in Table 1. A virtual brain tumor was defined as the region of interest (ROI) in the right brain (Fig. 1(b)). The other ROIs such as both brain hemispheres, eyes, optic nerves, and the brain stem were also defined as the soft tissue element. We performed a simulation of the irradiation of the brain tumor using BNCT and evaluated the dose for each ROI. To evaluate the total weighted dose for each ROI, the boron concentrations and reaction-dependent biological weighting factors were assumed to be realistic values applied to actual clinical trials conducted in the reactor-based BNCT (Nakai et al., 2009). Each value applied to the simulation is shown in Table 3. In this simulation, we considered the BNCT treatment with boronophenylalanine (BPA). Compound biological effectiveness (CBE) factors are dependent on the type of boron carrier. The CBE factor for tumor with BPA used was 3.8. Further, the relative biological effectiveness (RBE) values for fast neutrons, thermal neutrons, and photons were also set as 2.5, 2.5, and1.0, respectively. In this simulation, we set the total weighted dose given to the normal brain tissue to a maximum of 13 Gy-weighted (Gyw). The three-dimensional distributions for each dose component and the dose volume histogram (DVH) for each ROI were determined. The epithermal neutron beam of JRR-4 was used as the BNCT beam, and