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Original paper

Development of Monte Carlo based real-time treatment planning system with fast calculation algorithm for boron neutron capture therapy

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ABSTRACT

Purpose: We simulated the effect of patient displacement on organ doses in boron neutron capture therapy (BNCT). In addition, we developed a faster calculation algorithm (NCT high-speed) to simulate irradiation more efficiently.

Methods: We simulated dose evaluation for the standard irradiation position (reference position) using a head phantom. Cases were assumed where the patient body is shifted in lateral directions compared to the reference position, as well as in the direction away from the irradiation aperture.

For three groups of neutron (thermal, epithermal, and fast), flux distribution using NCT high-speed with a voxelized homogeneous phantom was calculated. The three groups of neutron fluxes were calculated for the same conditions with Monte Carlo code. These calculated results were compared.

Results: In the evaluations of body movements, there were no significant differences even with shifting up to 9 mm in the lateral directions. However, the dose decreased by about 10% with shifts of 9 mm in a direction away from the irradiation aperture.

When comparing both calculations in the phantom surface up to 3 cm, the maximum differences between the fluxes calculated by NCT high-speed with those calculated by Monte Carlo code for thermal neutrons and epithermal neutrons were 10% and 18%, respectively. The time required for NCT high-speed code was about 1/10th compared to Monte Carlo calculation.

Conclusions: In the evaluation, the longitudinal displacement has a considerable effect on the organ doses.

Conclusions: We also achieved faster calculation of depth distribution of thermal neutron flux using NCT high-speed calculation code.

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1. Introduction

Boron neutron capture therapy (BNCT) has attracted attention as a cancer therapy method that can be implemented at the cellular level. To perform BNCT, a treatment planning system is used for irradiation simulations in a manner similar to other radiotherapies such as X-ray therapy and particle therapy. A team including researchers from the University of Tsukuba is now developing a new treatment planning system for BNCT (with the tentative name of Tsukuba Plan) using a Monte Carlo algorithm [1,2].

BNCT has characteristics that differ from X-ray or particle beam therapies, for example, the fact that a rotational gantry is not mounted. For this reason, since the irradiation position is aligned to the fixed irradiation aperture, there may be cases where maintaining a fixed patient body position will be difficult. In addition, because BNCT irradiation times are relatively long compared with those of other radiation therapy modalities, the extended immobilization can be uncomfortable for patients. Thus, patient displacement during irradiation can occur, and affect the organ dose (e.g., intra-fractional variation). In regards to the patient displacement during BNCT treatment, Wielopolski et al. evaluated the effect of the patient body shifting (0.5, 1.0, 2.0 cm) in the case of BNCT treatment for brain tumor [3]. An approach to raise the immobilization precision of the patients in BNCT has also been studied [4].

This research aims to establish more efficient BNCT treatment with a focus on the changes in the dose for a body displacement of less than 1 cm. Depending on the irradiation site and immobilization accuracy, body displacements less than 1 cm are contemplated as intra-fractional variation for radiation therapy [5,6]. If

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the dose to organs at risk (OARs) most often or target dose changes owing to intra-fractional variation in the treatment, a framework for evaluating those changes becomes necessary. In particular, real-time evaluation for OARs is necessary to improve BNCT treatment because the tolerance dose for OARs determines the irradiation time.

However, real-time evaluation is very difficult using conventional Monte Carlo calculations because of their time-consuming nature. Therefore, we also investigated the higher-speed calculation algorithm by using neutron diffusion theory.

2. Materials and methods

2.1. Evaluation of organ dose uncertainties owing to patient body movement

This simulation was carried out using a human body head phantom (PB-1, Kyoto Kagaku Co., Ltd) and the Tsukuba Plan [1,7]. The Tsukuba Plan can simulate dose distribution using alternative radiation source information to enable irradiation simulations of various BNCT irradiation fields. In this evaluation, we assumed that the therapy was carried out using the Japan Research Reactor No. 4 (JRR-4) epithermal neutron beam [8].

For cases where the patient's body could easily move, we performed an irradiation simulation for the left maxillary sinus with patients in the seated position. The target was assumed to be a tumor dominating the left maxillary sinus. For a situation where the irradiation method involved the phantom forehead touching a fixed aperture, the target center was set so that the conditions for the beam center to pass through are those of the standard position (reference position). We evaluated the maximum dose to the skin, the limiting factor of the irradiation time, and the minimum dose to the tumor from the dose volume histogram for each body position. Table 1 shows the parameters required for BNCT treatment such as boron concentration, compound biological effectiveness, and relative biological effectiveness from published literature regarding the JRR-4 beam [9]. In the reference position, the irradiation time until the skin tolerance dose becomes 15 Gy-weighted (Gyw) was determined. As shown in Fig. 1, patient body motion away from center of the beam was simulated at steps of 1.5 mm up to a distance of 9.0 mm to the left and right of the reference position (lateral displacements). Furthermore, body motions were also evaluated up to a distance of 9.0 mm from the aperture, with steps of 1 mm (longitudinal displacements). For a position shifted from the reference position, a simulation was performed wherein irradiation was performed for the same time as the irradiation time used for the reference position.

Table 1
Various parameters used in the dose evaluation.

Parameters	Tumor	Normal tissue	Skin
Boron concentration (ppm)	72	24	28.8
CBE*	3.8	1.35	2.5
RBE**	Hydrogen dose: 2.5 Nitrogen dose: 2.5 Gamma dose: 1.0		

* CBE: compound biological effectiveness.
** RBE: relative biological effectiveness.

The particle and heavy ion transport code system (PHITS) was selected as the Monte Carlo calculation code [10], and this code was executed using a high performance, parallel computer cluster. The dose distribution with three hundred million particle histories was calculated using the PHITS code for each position. For each body position, the calculations were performed five times with different initial random number seeds.

2.2. Development of a higher speed BNCT calculation algorithm, and neutron flux distribution calculation

Dose evaluation in real-time using Monte Carlo calculations of changes to dose distributions owing to patient body movement during BNCT irradiation is extremely difficult because it is very time consuming. Therefore, we developed a higher-speed BNCT calculation algorithm (NCT high-speed). The basic concept of this code is based on neutron diffusion theory [11]. In the algorithm, we divided the continuous neutron energies into multi-groups and calculated the spatial distribution of the neutrons by solving the fixed-source neutron diffusion equations. In this research, we adapted the eight energy groups used for neutron beam calculations. To develop the code, and to enable an adaptation of such calculations to BNCT dose calculations for a human body, readings of the human body voxel model were created by averaging pixel data of medical images.

The fixed source multi-group neutron diffusion problem can be written as

$$-\nabla \cdot D_g(r)\nabla\phi_g(r) + \Sigma_{t,g}(r)\phi_g(r) = \sum_{g'=1}^{G}\Sigma_{s,g'\to g}(r)\phi_{g'}(r) + Q_g(r)$$
$$g = 1, 2, \ldots, G. \quad (1)$$

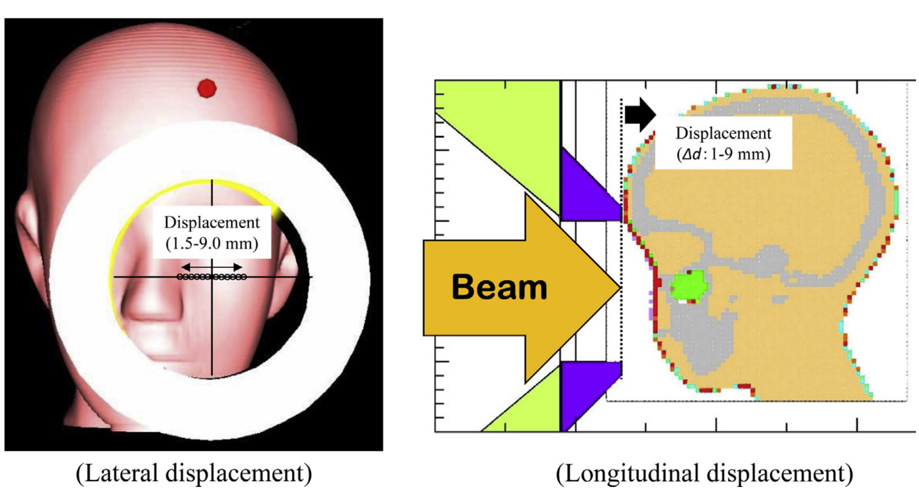

Fig. 1. Simulation geometry for the patient body motion. Δ*d:* the distance from the final collimator to the surface of the head phantom.

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where $\varnothing(r)$ and $Q(r)$ are the space (r) dependent group neutron flux and the external group neutron source, respectively, and $\Sigma_t(r), \Sigma_s(r)$, and $D(r)$ denote the space dependent total, scattering cross sections, and the spatial diffusion constant, respectively. These group constants are prepared so that Eq. (1) produces solutions close to the ones of the higher order neutron transport method. The left and right hand sides of Eq. (1) represent neutron loss and production terms, respectively. The first and second terms of the left hand side of Eq. (1) denote neutron loss from leakage and total removal from energy group g, respectively, while the first term at the right hand side denotes neutron production from scattering into energy group g.

The external group space-dependent neutron source is represented by $Q_g(r)$.

In the NCT high-speed method, we evaluated the depth distributions of group neutron flux within a $20 \times 20 \times 20$ cm cubic (8000 cm^3) homogenous phantom (0.5 cm cubic voxel model) consisting of soft tissue defined by the International Commission on Radiation Units and Measurements (density: 1.03 g/cm^3). For the neutron beam used in the evaluation, we used the above-mentioned JRR-4 epithermal neutron beam. The evaluation geometry is shown in Fig. 2. The neutron beam used in BNCT is a wide range continuous energy spectrum [12]. In the NCT high-speed method, we handled and calculated the energy structure as eight group structures, as shown in Table 2. We performed evaluations of depth distributions within the phantom, and compared them with the values calculated using PHITS, with regards to the neutron fluxes of three energy groups: fast neutrons, epithermal neutrons, and thermal neutrons. For the PHITS calculations, we implemented one hundred and fifty million particle histories for the same voxel model using a parallel computing system of 160 cores. This number of histories was determined by conditions that adequately reduce the statistical uncertainties (<3%) of the Monte Carlo calculation results up to a depth of 15 cm within the phantom. The calculation mesh size was set as 0.5 cm^3.

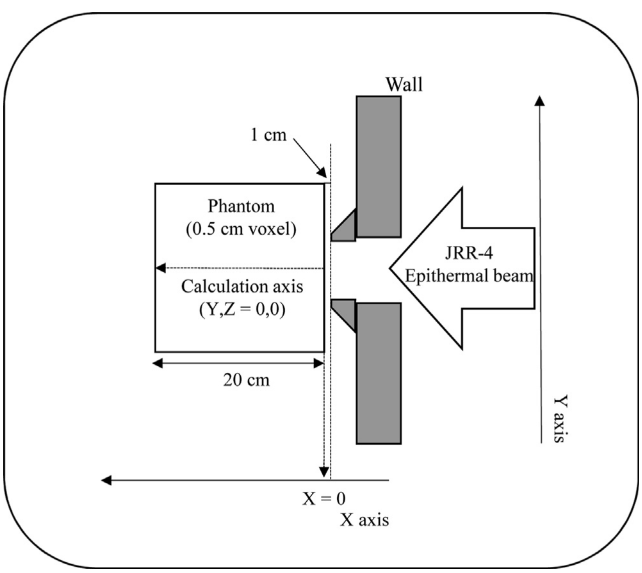

Fig. 2. Simulation geometry for comparison of the non-Monte Carlo calculation algorithm and the Monte Carlo calculations. The phantom consisted of homogeneous soft tissue.

Table 2
Neutron energy structure used in the high-speed calculation algorithm.

Group	Energy range (eV)	
1	8.21E+05	1.00E+07
2	6.74E+04	8.21E+05
3	1.23E+03	6.74E+04
4	1.76E+01	1.23E+03
5	6.83E−01	1.76E+01
6	2.77E−01	6.83E−01
7	8.53E−02	2.77E−01
8	1.00E−05	8.53E−02

3. Results

3.1. Calculation results of patient body movement in BNCT

The dose evaluations using PHITS related to body movement in the left and right directions are shown in Fig. 3. The evaluations related to body movement in a direction away from the irradiation aperture are shown in Fig. 4. When compared with the reference position dose, and considering the error owing to body movement in the lateral direction when shifting up to 9 mm from the reference position, the maximum skin dose and the minimum target dose were not significantly different. In contrast, the results related to body movement in a direction away from the aperture, when separated by 9 mm from the reference position, gave the maximum skin dose and the minimum target dose of 10.4% and 10.1% below the reference position dose, respectively.

3.2. Calculation result by NCT high-speed calculation algorithm for BNCT

Regarding the depth distribution of the three groups of neutron flux within a homogeneous phantom, the calculation result of the NCT high-speed method compared with the PHITS method is shown in Fig. 5. Both results were normalized by the values at the phantom surface.

The neutron fluxes for the three groups calculated using the NCT high-speed method showed the same trend as the depth distribution calculated with the PHITS method. However, large differences, in particular of the fast neutron flux, were seen in regions deeper than 3 cm in the phantom. To evaluate the dose for OARs, the thermal neutron and epithermal neutron flux are important. In shallow regions up to 3 cm from the phantom surface, the maximum differences between the fluxes calculated by the NCT high-speed method with those calculated by PHITS for thermal neutron and epithermal neutrons were 10% and 18%, respectively. In addition, the NCT high-speed method required only 2.3 min of computing time, while the PHITS method required 26.9 min.

4. Discussion

4.1. The impact of body movement on BNCT

Based on the evaluation results performed for BNCT in the seated position, we found that there was little effect on organ doses even with a position shift of several millimeters in either the left and right directions. However, there was a considerable effect on the doses if the position shifts in the direction moving away from the irradiation aperture. This is thought to be caused by beam divergence and the distance from the source to patient position.

While BNCT irradiation facilities can be divided into reactor-based and accelerator-based facilities, in either case various materials (moderators, shield) are distributed in the upper stream of the irradiation aperture [13,14]. There is a mutual interaction (mostly neutron scattering) between these materials and the neutrons, producing a non-zero angular distribution of components in the neutron beam; thus, the beam straightness is slightly distorted, especially in the case of accelerator-based BNCT.

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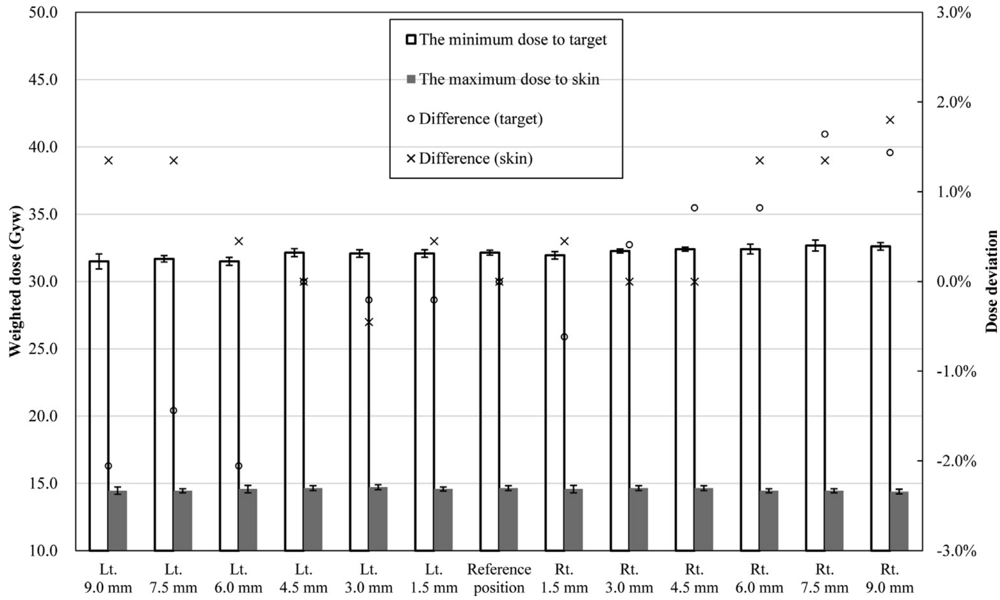

Fig. 3. Calculation results of dose variation for skin and target due to body motion in the lateral direction. Error bars show the statistical uncertainties by calculations with 5 times of Monte Carlo calculations. Bar graphs: weighted dose. Symbols: dose deviations in the case of lateral displacements compared to reference position.

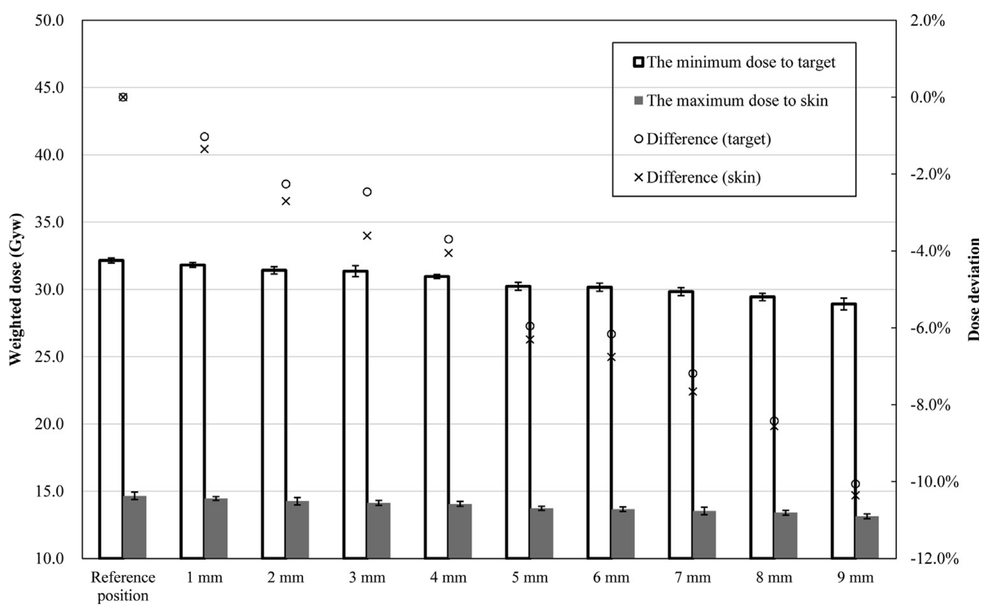

Fig. 4. Calculation results of dose variation for skin and target due to body motion of the direction away from the irradiation aperture. Error bars show the statistical uncertainties by calculations with 5 times of Monte Carlo calculations. Bar graphs: weighted dose. Symbols: dose deviations in the case of longitudinal displacements compared to reference position.

In our evaluation for longitudinal displacements, the relationship of Δd with the dose deviation for organ doses did not obey the inverse square law. The inverse square law is obeyed the total distance from the source to the patient with patient dose. The distance from the source to the final collimator depends on the BNCT facilities. Thus, the relationship between the patient longitudinal displacements with the dose also depends on the facilities.

4.2. The fast calculation algorithm for BNCT

In this evaluation, we adopted a calculation algorithm based on the multi-group neutron diffusion theory: the NCT high-speed method for BNCT evaluations. The BNCT dose calculation is commonly conducted by using a stochastic (Monte Carlo) method; however, the NCT high-speed method is a deterministic one, and is not based on the Monte Carlo method. When adapting to real world BNCT treatment planning, there is a need for the NCT high-speed method to perform particle transport calculations using a complex, realistic human head model. Fig. 6 shows the spatial distribution of the thermal neutron flux calculated with the NCT high-speed method with a realistic voxelized head phantom. This figure shows that the NCT high-speed method is able to calculate the three-dimensional spatial distribution of thermal neutron flux, even in complex shapes constructed from medical imaging data.

However, the calculation accuracy of the NCT high-speed method is inferior to the Monte Carlo method. Particularly, large differences were found in the deeper region of the phantom. In

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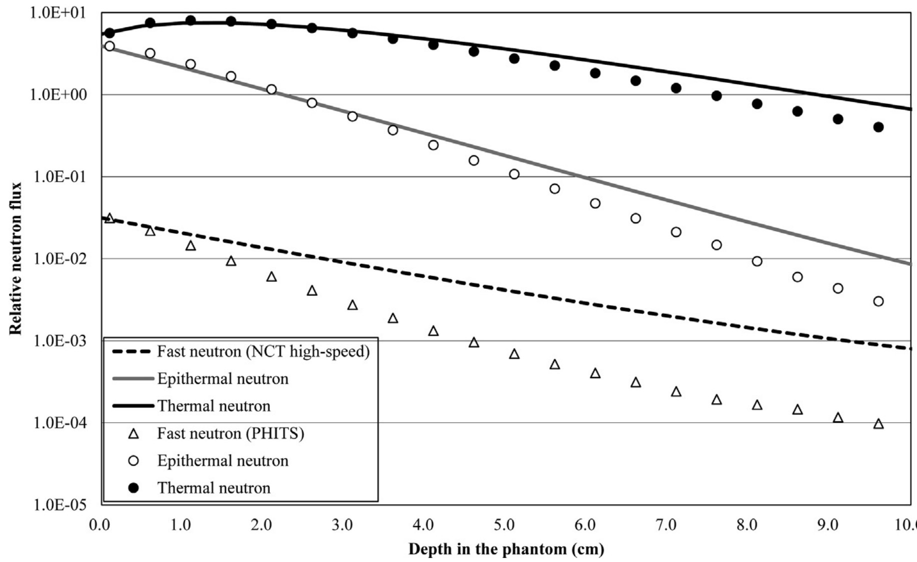

Fig. 5. Comparison of the results of the calculated depth distributions for the three groups of neutron flux in a homogeneous phantom. Lines indicate the results of the NCT-high speed method (non-Monte Carlo calculation), and symbols give the results of the Monte Carlo calculations.

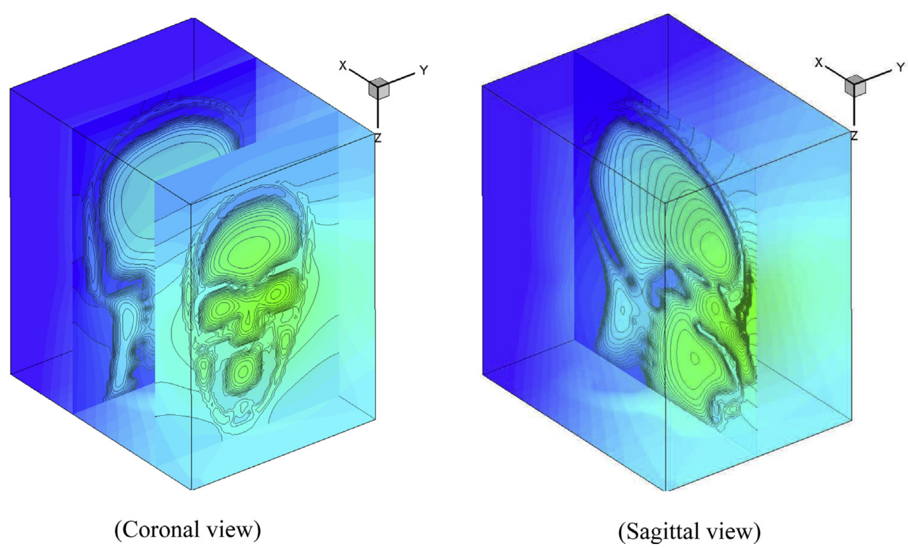

Fig. 6. Calculation results of the thermal neutron distributions using the NCT high-speed calculation algorithm in a complex human-shaped phantom model.

BNCT, the irradiation time is almost determined by the dose limitations of OARs such as skin and mucosa. If a patient position shift has occurred, the dose calculation should be performed again to these non-deep-sited organs with faster calculation. Therefore, it is thought that the NCT high-speed calculation can adapt to the shallow (e.g. superficial) regions under the present conditions.

In this research, calculation results for neutron fluxes were only represented, of course, the absorbed dose should be calculated using an energy-dependent coefficient factor from neutron flux.

4.3. Challenges to developing a real-time dose evaluation system for BNCT

Our final goal is to develop BNCT dose evaluations in real-time, however, a number of issues remain.

For example, the depth distributions of the thermal neutron flux within the homogeneous phantom, calculated with the NCT high-speed method, are not identical to the corresponding distributions calculated by the PHITS method. Thus, there is a need to enhance the calculation precision of the NCT high-speed method. One method to do this is by using more neutron energy groups than the current eight group structure. Because the calculation time will also increase when the energy structure is more detailed, there is a need to find a good balance between the calculation precision and the calculation time.

In addition, there is a need for a method of monitoring patient body movements during treatment, as well as a method that avoids patient body movement as much as possible. When such movements are unavoidable, the direction and the degree of movement should be measured and fed back into the system for dose re-evaluations. With the collection of this type of data, we expect that a real-time BNCT dose evaluation system can be realized.

5. Conclusion

In this research, we used the Monte Carlo calculation code PHITS to evaluate the effects of patient position shift on the skin

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and target doses during BNCT treatment. The results showed that the effect of lateral position shift is small, but that the organ doses changes considerably with distance changes in the direction away from the irradiation aperture.

In addition, we introduced the principles and the present development status concerning a high-speed calculation algorithm, the NCT high-speed method, which can achieve relatively high-speed BNCT calculations as compared to Monte Carlo calculations. In the future, we plan to implement further refinements to enhance the possibility of realizing real-time BNCT dose evaluations.

Conflict of interest

The authors report no conflicts of interest.

Acknowledgements

Numerical calculations were performed in part using the Cluster of Many-core Architecture processor (COMA) at the Center for Computational Sciences, University of Tsukuba.

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