



## Original Article

# Evaluation of the medical staff effective dose during boron neutron capture therapy using two high resolution voxel-based whole body phantoms

Mohadeseh Golshanian <sup>a, b</sup>, Ali Akbar Rajabi <sup>a, c</sup>, Yaser Kasesaz <sup>b,\*</sup><sup>a</sup> Department of Physics, Shahrood University, Shahrood, Iran<sup>b</sup> Reactor and Nuclear Safety Research School, Nuclear Science and Technology Research Institute (NSTRI), Tehran, Iran<sup>c</sup> Shams Institute of Higher Education, Gonbad, Iran

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## ABSTRACT

Because accelerator-based boron neutron capture therapy (BNCT) systems are planned for use in hospitals, entry into the medical room should be controlled as hospitals are generally assumed to be public and safe places. In this paper, computational investigation of the medical staff effective dose during BNCT has been performed in different situations using Monte Carlo N-Particle (MCNP4C) code and two voxel based male phantoms. The results show that the medical staff effective dose is highly dependent on the position of the medical staff. The results also show that the maximum medical staff effective dose in an emergency situation in the presence of a patient is ~25.5 µSv/s.

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## 1. Introduction

Boron neutron capture therapy (BNCT) is a method of external radiotherapy [1]. In this method, after labeling the cancer cells with the 10-boron carrier drug, cancer cells will be irradiated with low-energy thermal neutrons. The released high energy  $\alpha$  and  $^{7}\text{Li}$  particles from the  $^{10}\text{B}(\text{n},\alpha)^{7}\text{Li}$  reaction can destroy the cancer cells [2]. Neutron sources for BNCT currently have been limited to nuclear research reactors such as FIR1 in Finland [3], THOR in Taiwan [4], and JRR4 in Japan [5]. Nowadays, accelerator-based neutron sources for hospital based BNCT facilities are being focused on to develop the BNCT technique as a routine radiation therapy [6–8].

The typical BNCT treatment time is ~15–45 minutes [2]. During the irradiation time, a 20–25 Gy-eq dose will be delivered to the tumor tissue [2].

From a radiation protection point of view, the effective dose to the patient during BNCT should be known because excessive radiation exposure can potentially cause cancer and genetic defects [9]. There are some published works related to assessment of the patient effective dose during BNCT [10–12], but our knowledge regarding the effective dose to the medical staff (or any other

healthcare workers) in emergency situations in which the medical staff need to be in the irradiation room during BNCT is poor. The main objective of this research is to evaluate the medical staff effective dose during BNCT. To do this, the BNCT neutron beam of the Tehran Research Reactor (TRR) has been considered as a typical BNCT beam [12], and, using the MCNP4C Monte Carlo code [13], two whole body voxel-based male phantoms have been simulated simultaneously to represent the patient and the medical staff, as shown in Fig. 1. Two different situations have been studied: (1) Situation 1, the patient is not in the irradiation room and the neutron beam port is not closed; and (2) Situation 2, both the patient and medical staff are in the irradiation room.

In each situation, the effective dose to medical staff has been calculated in four different positions, as shown in Fig. 1.

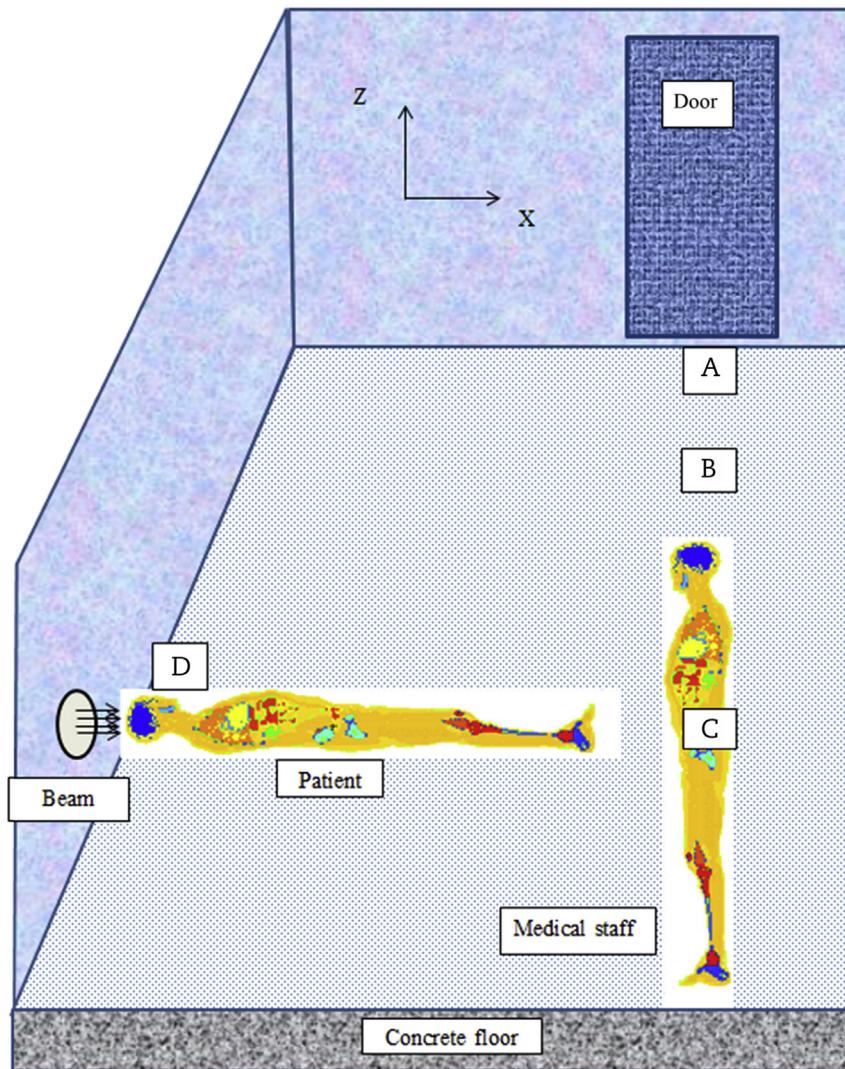
## 2. Materials and methods

### 2.1. Neutron beam properties

As mentioned above, a typical BNCT beam has been used in this study; its characterization is described in detail in Ref. [12]. The neutron and gamma sources have been defined as the surface sources which are divided into 10 regions, as shown in Fig. 2. Each region has its own neutron and gamma specifications, which are

\* Corresponding author.

E-mail address: [ykasesaz@aeoi.org.ir](mailto:ykasesaz@aeoi.org.ir) (Y. Kasesaz).



**Fig. 1.** Schematic view of the patient and medical staff positions in the medical room. All calculations have been done for A, B, C, and D positions of the medical staff for two situations: (1) medical staff is alone in the medical room; and (2) medical staff and patient are in the medical room simultaneously.

presented in Table 1 [12]. These neutron and gamma data have been defined as the neutron and gamma sources for dose calculation in the two separate MCNP input files.

## 2.2. The voxel-based phantom

The voxel-based phantom has been used according to the International Commission on Radiological Protection (ICRP) publication 110 [14].

The ICRP 110 male phantom is 177.6 cm in height and 73 kg in weight. It includes  $254 \times 127 \times 222$  voxels. The size of each voxel is  $2.137 \times 2.137 \times 8$  mm<sup>3</sup>. A total of 141 different organ/tissue and 53 different tissue materials have been defined in the phantom. Fig. 1 provides a sectional view of the MCNP model of this phantom. The properties of some organs of the phantom are presented in Table 2 [14]. To calculate the medical staff effective dose in Situation 1, two separate phantoms have been modeled simultaneously as the patient and the medical staff.

## 2.3. Calculation description

To calculate the medical staff effective dose, at first, the absorbed dose rates due to neutron and gamma radiation were

determined separately for the 27 organs in the medical staff phantom (Table 2) using F6:n and F6:p MCNP cards. It is remarkable that the gamma dose is due to two components: primary gamma rays that are present in the beam line and secondary gamma rays that are induced in the tissues. These two gamma dose components have been calculated separately.

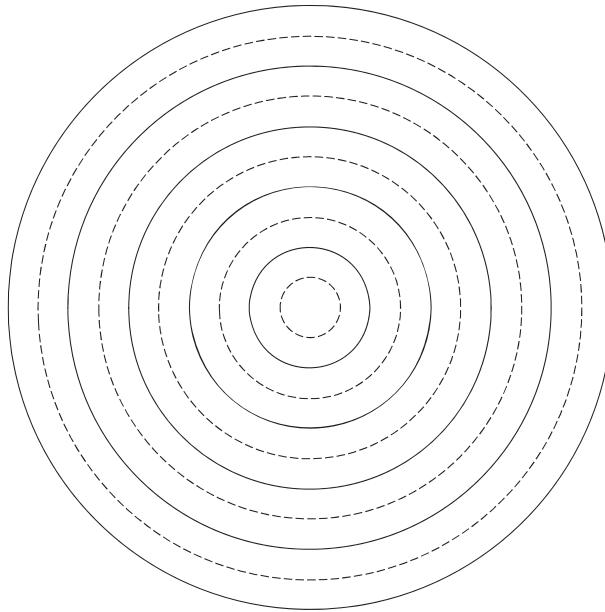
In the next steps, the equivalent dose and the effective dose have been calculated. The equivalent dose,  $H_T$  (Sv/s), is defined as [15]:

$$H_T = \sum_R W_R D_{T,R} \quad (1)$$

where  $D_{T,R}$  (Gy/s) is the average absorbed dose rate due to radiation of type R in the volume of a specific organ T and  $W_R$  is the radiation weighting factor of radiation of type R. According to ICRP 103 [15], the  $W_R$  for gamma radiation is equal to 1 and for neutron radiation is as follows [15]:

$$W_R(E) = \begin{cases} 2.5 + 18.2e^{-[ln(E)]^2/6}; & E < 1 \text{ MeV} \\ 5.0 + 17.0e^{-[ln(E)]^2/6}; & 1 \text{ MeV} < E < 50 \text{ MeV} \end{cases} \quad (2)$$

where E is the neutron energy (MeV). In order to consider this continuous  $W_R$  function for neutron dose, F6/DE6/DF6 MCNP cards were used to calculate the following quantity:



**Fig. 2.** Ten regions of neutron and gamma surface source [9].

**Table 1**  
Parameters of the used neutron source.

Source particle	Source strength ( $\times 10^{10} \text{ s}^{-1}$ )									
	Beam radius (cm)									
	0–1	1–2	2–3	3–4	4–5	5–6	6–7	7–8	8–9	9–10
Neutron	Thermal	0.01	0.03	0.04	0.05	0.05	0.05	0.06	0.07	0.10
	Epithermal	0.28	0.80	1.14	1.35	1.53	1.62	1.68	1.73	1.83
	Fast	0.08	0.24	0.34	0.41	0.47	0.51	0.54	0.57	0.62
	Total	0.37	1.07	1.52	1.81	2.05	2.18	2.28	2.38	2.47
Gamma		0.02	0.06	0.07	0.05	0.04	0.03	0.02	0.02	0.01

**Table 2**  
Characteristics and weighting factors of certain organs based on ICRP 110 voxel phantom.

Organs	Density ( $\text{g cm}^{-3}$ )	Mass (g)	Organ weighting factor
Lung	0.42	1,200	0.12
Stomach	1.04	150.0	0.12
Colon	1.04	527	0.12
Bone marrow (red)	1.03	1,170	0.12
Breast	0.98	25.0	0.12
Gonads	1.04	35.0	0.08
Thyroid	1.04	20.0	0.04
Esophagus	1.03	40.0	0.04
Bladder	1.04	200	0.04
Liver	1.04	1,800	0.04
Bone surface	1.91	4,400	0.01
Skin	1.09	3,728.0	0.01
Brain	1.05	1,450.0	0.01
Salivary glands	1.03	85.0	0.01
Reminder organs:			
Adrenals	1.03	14.0	0.12
Gall bladder	1.03	13.9	0.12
Heart	1.05	330.0	0.12
Kidneys	1.05	310.0	0.12
Lymphatic tissue	1.03	138.0	0.12
Muscle	1.05	29,000.0	0.12
Pancreas	1.05	140.0	0.12
Prostate	1.03	17.0	0.12
Small intestine	1.04	650.0	0.12
Spleen	1.04	150.0	0.12
Thymus	1.03	25.0	0.12

ICRP, International Commission on Radiological Protection.

$$\int D_{T,R}(E)W_R(E)dE \quad (3)$$

The effective dose rate,  $E$  (Sv/s), is equal to the sum of equivalent dose ( $H_T$ ) multiplied by the tissue weighting factors according to the following equation:

$$E = \sum_T W_T H_T \quad (4)$$

where  $W_T$  is the tissue/organ weighting factor (Table 2 [15]).

It is remarkable that, to acquire acceptable statistical error (~5%),  $10^8$  particle histories were employed in all calculations.

#### 2.4. Considered positions of the medical staff

As mentioned above, in each situation, the medical staff effective dose has been calculated in four different positions in the treatment room, as follows (see Fig. 1): (1) near the door of the irradiation room (facing  $-y$  direction, centered at  $x = 0 y = 262 z = -44$ ); (2) at the center of the irradiation room (facing  $-y$  direction, centered at  $x = 0 y = 145 z = -44$ ); (3) at 200 cm from the beam port (facing  $-x$  direction, centered at  $y = 27.13 z = -44$ ); and (4) close to the beam port on the left side of the patient (facing  $-y$  direction, centered at  $x = -42 y = 43 z = -44$ ). The dimensions of the treatment room were estimated as follows: centered at  $x_{\min} = -100$ :  $x_{\max} = 400$ ,  $y_{\min} = -90$ :  $y_{\max} = 290$ ,  $z_{\min} = -45$ :  $z_{\max} = 273$ .

To consider possible scattered neutron and gamma particles from the irradiation room walls and floor, a 35-cm thickness of concrete has been assumed for walls and floor.

### 3. Results

#### 3.1. Organ absorbed dose of medical staff

The calculated absorbed doses for desired organs (Table 2) related to Situations 1 and 2 are presented in Tables 3 and 4, respectively. The results show that: (1) for both situations, the gamma absorbed dose is higher than the neutron absorbed dose in positions (A), (B), and (C) for most organs. This gamma dose is due to secondary gamma rays, which are produced from neutron interaction within the tissues (~90% of the total gamma dose); (2) for both situations, at points (A) and (B), gonads, bladder, and stomach have the maximum value of gamma absorbed dose. The gonad doses in Situation 1 are 0.33  $\mu\text{Gy/s}$  and 0.85  $\mu\text{Gy/s}$  at points A and B, respectively, and in Situation 2 are 1.2  $\mu\text{Gy/s}$  and 3.32  $\mu\text{Gy/s}$ ; (3) at point C in Situation 1, both neutron absorbed dose (0.45 mGy/s) and gamma absorbed dose (1 mGy/s) have their highest values in the bladder, although in Situation 2 the gonads have the highest values of both neutron absorbed dose (0.2  $\mu\text{Gy/s}$ ) and gamma absorbed dose (1.5  $\mu\text{Gy/s}$ ); and (4) at point D in Situation 1, skin, reminder organs, and bone surface have the maximum value of neutron absorbed dose, whereas the gonads have the maximum value of gamma absorbed dose. In Situation 2, the maximum gamma and neutron absorbed doses are related to reminder organs (0.4  $\mu\text{Gy/s}$ ) and skin (5  $\mu\text{Gy/s}$ ), respectively.

#### 3.2. Organ equivalent dose

Table 5 presents the calculated values of  $H_T$  for Situations 1 and 2. The results in Table 5 indicate that: (1) at points A and B, the breast has the highest and the reminder has the lowest value of  $H_T$  in both situations. The breast doses in Situation 1 are 1.96  $\mu\text{Sv/s}$  and 3.35  $\mu\text{Sv/s}$  at points A and B, respectively; in Situation 2 these

**Table 3**Absorbed dose rate,  $D_T$  (Gy/s), for desired organs of the medical staff in Situation 1 at A, B, C, and D positions (see Fig. 1).

Organs/tissues	Neutron	Secondary gamma	Primary gamma	Total gamma	Total
Lung					
A	2.46E–08	2.07E–07	2.00E–10	2.08E–07	2.32E–07
B	5.69E–08	4.92E–07	7.31E–10	4.93E–07	5.50E–07
C	1.72E–07	1.34E–05	4.38E–08	1.34E–05	1.36E–05
D	1.86E–07	2.35E–06	8.63E–09	2.36E–06	2.55E–06
Stomach					
A	3.20E–08	2.81E–07	2.26E–10	2.82E–07	3.14E–07
B	9.99E–08	7.41E–07	8.89E–10	7.42E–07	8.42E–07
C	6.50E–07	4.45E–05	1.33E–07	4.47E–05	4.53E–05
D	1.29E–07	3.13E–06	1.10E–08	3.14E–06	3.27E–06
Colon					
A	3.49E–08	2.64E–07	2.66E–10	2.64E–07	2.99E–07
B	1.04E–07	7.11E–07	9.91E–10	7.12E–07	8.16E–07
C	5.88E–05	2.16E–04	1.53E–05	1.71E–04	2.31E–04
D	2.98E–07	4.04E–06	2.64E–08	4.06E–06	4.36E–06
Bone marrow (red)					
A	2.18E–08	1.92E–07	2.00E–10	1.93E–07	2.15E–07
B	5.44E–08	4.88E–07	7.48E–10	4.89E–07	5.43E–07
C	2.86E–05	1.56E–04	8.55E–06	1.64E–04	1.93E–04
D	3.80E–07	3.93E–06	2.57E–08	3.95E–06	4.33E–06
Breast					
A	1.21E–07	2.57E–07	3.04E–10	2.58E–07	3.78E–07
B	2.47E–07	5.79E–07	1.38E–09	5.81E–07	8.28E–07
C	6.30E–07	1.61E–05	4.47E–08	1.61E–05	1.68E–05
D	8.34E–08	1.23E–06	3.43E–09	1.23E–06	1.32E–06
Gonads					
A	6.48E–08	3.29E–07	3.01E–10	3.30E–07	3.94E–07
B	2.21E–07	8.47E–07	1.04E–09	8.48E–07	1.07E–06
C	3.07E–06	1.01E–04	3.15E–07	1.01E–04	1.04E–04
D	7.96E–08	2.61E–06	1.50E–08	2.62E–06	2.70E–06
Thyroid					
A	7.91E–08	2.71E–07	3.03E–10	2.71E–07	3.50E–07
B	2.03E–07	5.74E–07	1.19E–09	5.75E–07	7.78E–07
C	4.34E–07	5.99E–06	2.24E–08	6.01E–06	6.44E–06
D	2.15E–08	9.23E–07	2.56E–09	9.26E–07	9.47E–07
Esophagus					
A	2.80E–08	1.93E–07	2.11E–10	1.93E–07	2.21E–07
B	6.05E–08	4.92E–07	7.27E–10	4.92E–07	5.53E–07
C	1.92E–07	1.39E–05	4.52E–08	1.40E–05	1.42E–05
D	7.14E–08	2.08E–06	8.13E–09	2.09E–06	2.16E–06
Bladder					
A	3.24E–08	2.99E–07	2.64E–10	2.99E–07	3.32E–07
B	9.58E–08	7.61E–07	1.09E–09	7.62E–07	8.58E–07
C	4.51E–04	8.96E–04	1.00E–04	9.96E–04	1.45E–03
D	2.24E–07	4.65E–06	3.68E–08	4.69E–06	4.92E–06
Liver					
A	2.75E–08	2.39E–07	2.16E–10	2.39E–07	2.66E–07
B	6.19E–08	5.49E–07	8.88E–10	5.50E–07	6.12E–07
C	4.80E–07	3.77E–05	1.23E–07	3.78E–05	3.83E–05
D	1.31E–07	2.39E–06	1.44E–08	2.41E–06	2.54E–06
Bone surface					
A	2.67E–08	1.90E–07	2.05E–10	1.90E–07	2.17E–07
B	6.83E–08	5.03E–07	7.67E–10	5.04E–07	5.72E–07
C	1.76E–05	9.90E–05	5.25E–06	1.04E–04	1.22E–04
D	4.48E–07	3.34E–06	2.10E–08	3.36E–06	3.80E–06
Skin					
A	6.54E–08	1.45E–07	2.25E–10	1.45E–07	2.10E–07
B	1.82E–07	3.86E–07	8.36E–10	3.87E–07	5.69E–07
C	2.74E–05	4.38E–05	2.48E–06	4.63E–05	7.37E–05
D	2.01E–06	2.51E–06	2.97E–08	2.54E–06	4.55E–06
Brain					
A	1.52E–08	1.17E–07	1.49E–10	1.18E–07	1.33E–07
B	3.75E–08	2.77E–07	5.57E–10	2.78E–07	3.15E–07
C	8.56E–08	1.82E–06	8.46E–09	1.83E–06	1.91E–06
D	8.86E–08	6.93E–07	1.55E–09	6.94E–07	7.83E–07
Salivary glands					
A	4.54E–08	1.86E–07	1.98E–10	1.86E–07	2.32E–07
B	1.16E–07	4.11E–07	8.57E–10	4.12E–07	5.28E–07
C	2.52E–07	3.35E–06	1.46E–08	3.36E–06	3.61E–06
D	8.56E–08	6.37E–07	1.04E–09	6.38E–07	7.24E–07
Reminder					
A	1.01E–08	1.46E–07	1.38E–10	1.46E–07	1.56E–07
B	1.34E–08	4.26E–07	7.14E–10	4.27E–07	4.40E–07
C	2.77E–07	3.70E–05	1.69E–07	3.72E–05	3.74E–05
D	9.16E–07	6.99E–06	2.83E–08	7.02E–06	7.94E–06

**Table 4**

Absorbed dose rate, (Gy/s), for desired organs of the medical staff in Situation 2 at A, B, C, and D positions (see Fig. 1).

Organs/tissues	Neutron	Secondary gamma	Primary gamma	Total gamma	Total
Lung					
A	5.28E–08	8.17E–07	4.22E–09	8.21E–07	8.73E–07
B	1.29E–07	2.01E–06	1.26E–08	2.02E–06	2.15E–06
C	5.87E–08	8.44E–07	3.91E–08	8.83E–07	9.42E–07
D	6.23E–07	1.44E–05	9.99E–08	1.45E–05	1.51E–05
Stomach					
A	7.02E–08	1.07E–06	5.20E–09	1.08E–06	1.15E–06
B	2.20E–07	2.92E–06	1.64E–08	2.94E–06	3.16E–06
C	6.46E–08	9.70E–07	3.56E–08	1.01E–06	1.07E–06
D	4.98E–07	1.95E–05	1.19E–07	1.97E–05	2.02E–05
Colon					
A	7.83E–08	1.04E–06	5.31E–09	1.05E–06	1.13E–06
B	2.30E–07	2.76E–06	1.67E–08	2.78E–06	3.01E–06
C	6.77E–08	9.16E–07	7.08E–08	9.86E–07	1.05E–06
D	8.02E–07	2.29E–05	2.29E–07	2.31E–05	2.39E–05
Bone marrow (red)					
A	4.52E–08	7.79E–07	4.25E–09	7.84E–07	8.29E–07
B	1.19E–07	2.00E–06	1.26E–08	2.01E–06	2.13E–06
C	4.78E–08	7.72E–07	6.01E–08	8.32E–07	8.80E–07
D	9.61E–07	2.12E–05	2.24E–07	2.15E–05	2.24E–05
Breast					
A	1.83E–07	1.09E–06	6.82E–09	1.09E–06	1.28E–06
B	5.09E–07	2.63E–06	2.09E–08	2.66E–06	3.16E–06
C	1.68E–07	1.11E–06	5.48E–08	1.17E–06	1.34E–06
D	2.71E–07	8.22E–06	3.73E–08	8.26E–06	8.53E–06
Gonads					
A	1.44E–07	1.20E–06	6.31E–09	1.20E–06	1.35E–06
B	4.32E–07	3.30E–06	2.02E–08	3.32E–06	3.76E–06
C	1.87E–07	1.44E–06	2.82E–08	1.46E–06	1.65E–06
D	2.72E–07	1.66E–05	1.38E–07	1.68E–05	1.71E–05
Thyroid					
A	1.80E–07	1.08E–06	6.43E–09	1.09E–06	1.27E–06
B	3.79E–07	2.53E–06	1.87E–08	2.55E–06	2.93E–06
C	1.66E–07	1.21E–06	5.30E–08	1.26E–06	1.43E–06
D	7.20E–08	6.73E–06	3.03E–08	6.76E–06	6.83E–06
Esophagus					
A	5.90E–08	8.12E–07	4.28E–09	8.16E–07	8.75E–07
B	1.29E–07	1.98E–06	1.25E–08	1.99E–06	2.12E–06
C	6.35E–08	8.46E–07	3.93E–08	8.86E–07	9.49E–07
D	2.84E–07	1.31E–05	8.71E–08	1.32E–05	1.35E–05
Bladder					
A	7.45E–08	1.16E–06	4.28E–09	1.17E–06	1.24E–06
B	2.16E–07	2.97E–06	1.25E–08	2.98E–06	3.20E–06
C	3.74E–08	8.60E–07	3.93E–08	1.17E–06	1.21E–06
D	4.74E–07	2.53E–05	8.71E–08	2.57E–05	2.61E–05
Liver					
A	4.91E–08	8.73E–07	4.53E–09	8.78E–07	9.27E–07
B	1.16E–07	2.08E–06	1.37E–08	2.10E–06	2.21E–06
C	5.84E–08	8.85E–07	3.33E–08	9.19E–07	9.77E–07
D	2.79E–07	1.30E–05	1.43E–07	1.31E–05	1.34E–05
Bone surface					
A	5.61E–08	8.07E–07	4.49E–09	8.12E–07	8.68E–07
B	1.50E–07	2.12E–06	1.31E–08	2.13E–06	2.28E–06
C	7.26E–08	9.47E–07	5.20E–08	9.99E–07	1.07E–06
D	1.13E–06	1.95E–05	1.85E–07	1.97E–05	2.08E–05
Skin					
A	1.39E–07	7.30E–07	4.80E–09	7.34E–07	8.74E–07
B	3.97E–07	1.93E–06	1.41E–08	1.95E–06	2.34E–06
C	1.86E–07	8.45E–07	4.33E–08	8.89E–07	1.07E–06
D	4.82E–06	2.08E–05	2.42E–07	2.10E–05	2.58E–05
Brain					
A	3.02E–08	5.48E–07	3.19E–09	5.51E–07	5.82E–07
B	7.38E–08	1.31E–06	9.11E–09	1.32E–06	1.40E–06
C	4.59E–08	6.88E–07	3.49E–08	7.23E–07	7.69E–07
D	2.34E–07	4.52E–06	2.23E–08	4.54E–06	4.77E–06
Salivary glands					
A	9.02E–08	7.90E–07	4.71E–09	7.94E–07	8.84E–07
B	2.48E–07	1.89E–06	1.45E–08	1.90E–06	2.15E–06
C	1.06E–07	9.30E–07	4.88E–08	9.79E–07	1.08E–06
D	2.52E–07	4.43E–06	1.38E–08	4.45E–06	4.70E–06
Reminder					
A	7.92E–09	5.90E–07	2.76E–09	5.93E–07	6.01E–07
B	3.96E–08	1.72E–06	9.79E–09	1.73E–06	1.77E–06
C	1.32E–08	5.46E–07	2.12E–08	5.67E–07	5.80E–07
D	2.82E–06	3.81E–05	2.85E–07	3.84E–05	4.12E–05

**Table 5**Equivalent dose rate,  $H_T$  (Sv/s), for desired organs of the medical staff in Situations 1 and 2 at A, B, C, and D positions (see Fig. 1).

Organs/tissues	Neutron $W_R = W_R(E)$	Gamma $W_R = 1$	Total	Neutron $W_R = W_R(E)$	Gamma $W_R = 1$	Total
	Situation 1	Situation 2				
<b>Lung</b>						
A	1.71E–07	2.08E–07	3.79E–07	3.32E–07	8.21E–07	1.15E–06
B	3.62E–07	4.93E–07	8.55E–07	7.93E–07	2.02E–06	2.81E–06
C	1.47E–06	1.34E–05	1.49E–05	2.78E–07	8.83E–07	1.16E–06
D	1.19E–06	2.36E–06	3.55E–06	3.80E–06	1.45E–05	1.83E–05
<b>Stomach</b>						
A	2.43E–07	2.82E–07	5.25E–07	4.65E–07	1.08E–06	1.55E–06
B	8.03E–07	7.42E–07	1.55E–06	1.56E–06	2.94E–06	4.50E–06
C	5.13E–06	4.47E–05	4.98E–05	3.64E–07	1.01E–06	1.37E–06
D	8.22E–07	3.14E–06	3.96E–06	3.14E–06	1.97E–05	2.28E–05
<b>Colon</b>						
A	2.70E–07	2.64E–07	5.34E–07	5.42E–07	1.05E–06	1.59E–06
B	8.17E–07	7.12E–07	1.53E–06	1.64E–06	2.78E–06	4.42E–06
C	7.15E–04	2.31E–04	9.46E–04	4.03E–07	9.86E–07	1.39E–06
D	2.38E–06	4.06E–06	6.44E–06	6.02E–06	2.31E–05	2.91E–05
<b>Bone marrow (red)</b>						
A	1.80E–07	1.93E–07	3.73E–07	3.28E–07	7.84E–07	1.11E–06
B	4.29E–07	4.89E–07	9.18E–07	8.67E–07	2.01E–06	2.88E–06
C	3.33E–04	1.64E–04	4.97E–04	2.99E–07	8.32E–07	1.13E–06
D	3.04E–06	3.95E–06	6.99E–06	7.27E–06	2.15E–05	2.88E–05
<b>Breast</b>						
A	1.70E–06	2.58E–07	1.96E–06	2.26E–06	1.09E–06	3.35E–06
B	2.95E–06	5.81E–07	3.53E–06	6.21E–06	2.66E–06	8.87E–06
C	8.10E–06	1.61E–05	2.42E–05	1.71E–06	1.17E–06	2.88E–06
D	1.07E–06	1.23E–06	2.30E–06	3.53E–06	8.26E–06	1.18E–05
<b>Gonads</b>						
A	5.62E–07	3.30E–07	8.92E–07	1.14E–06	1.20E–06	2.34E–06
B	2.39E–06	8.48E–07	3.24E–06	3.76E–06	3.32E–06	7.08E–06
C	2.65E–05	1.01E–04	1.28E–04	1.32E–06	1.46E–06	2.78E–06
D	5.75E–07	2.62E–06	3.20E–06	2.27E–06	1.68E–05	1.91E–05
<b>Thyroid</b>						
A	7.71E–07	2.71E–07	1.04E–06	1.74E–06	1.09E–06	2.83E–06
B	2.21E–06	5.75E–07	2.79E–06	3.12E–06	2.55E–06	5.67E–06
C	4.49E–06	6.01E–06	1.05E–05	1.08E–06	1.26E–06	2.34E–06
D	1.25E–07	9.26E–07	1.05E–06	3.31E–07	6.76E–06	7.09E–06
<b>Esophagus</b>						
A	2.40E–07	1.93E–07	4.33E–07	5.03E–07	8.16E–07	1.32E–06
B	4.74E–07	4.92E–07	9.66E–07	8.18E–07	1.99E–06	2.81E–06
C	1.85E–06	1.40E–05	1.59E–05	3.47E–07	8.86E–07	1.23E–06
D	2.95E–07	2.09E–06	2.39E–06	1.71E–06	1.32E–05	1.49E–05
<b>Bladder</b>						
A	2.02E–07	2.99E–07	5.01E–07	4.86E–07	1.17E–06	1.66E–06
B	6.92E–07	7.62E–07	1.45E–06	1.55E–06	2.98E–06	4.53E–06
C	5.52E–03	9.96E–04	6.52E–03	1.69E–07	1.17E–06	1.34E–06
D	1.72E–06	4.69E–06	6.41E–06	3.85E–06	2.57E–05	2.96E–05
<b>Liver</b>						
A	1.90E–07	2.39E–07	4.29E–07	2.86E–07	8.78E–07	1.16E–06
B	4.33E–07	5.50E–07	9.83E–07	7.44E–07	2.10E–06	2.84E–06
C	3.58E–06	3.78E–05	4.14E–05	2.76E–07	9.19E–07	1.20E–06
D	8.62E–07	2.41E–06	3.27E–06	1.98E–06	1.31E–05	1.51E–05
<b>Bone surface</b>						
A	2.46E–07	1.90E–07	4.36E–07	4.67E–07	8.12E–07	1.28E–06
B	6.11E–07	5.04E–07	1.12E–06	1.23E–06	2.13E–06	3.36E–06
C	2.05E–04	1.04E–04	3.09E–04	5.59E–07	9.99E–07	1.56E–06
D	4.29E–06	3.36E–06	7.65E–06	9.49E–06	1.97E–05	2.92E–05
<b>Skin</b>						
A	7.07E–07	1.45E–07	8.52E–07	1.26E–06	7.34E–07	1.99E–06
B	1.99E–06	3.87E–07	2.38E–06	3.63E–06	1.95E–06	5.58E–06
C	3.75E–04	4.63E–06	3.80E–04	1.51E–06	8.89E–07	2.40E–06
D	2.42E–05	2.54E–06	2.67E–05	4.71E–05	2.10E–05	6.81E–05
<b>Brain</b>						
A	1.38E–07	1.18E–07	2.56E–07	2.50E–07	5.51E–07	8.01E–07
B	3.26E–07	2.78E–07	6.04E–07	6.06E–07	1.32E–06	1.93E–06
C	8.82E–07	1.83E–06	2.71E–06	3.70E–07	7.23E–07	1.09E–06
D	7.93E–07	6.94E–07	1.49E–06	1.75E–06	4.54E–06	6.29E–06
<b>Salivary glands</b>						
A	4.72E–07	1.86E–07	6.58E–07	8.31E–07	7.94E–07	1.63E–06
B	1.07E–06	4.12E–07	1.48E–06	2.12E–06	1.90E–06	4.02E–06
C	2.47E–06	3.36E–06	5.83E–06	7.86E–07	9.79E–07	1.77E–06
D	7.08E–07	6.38E–07	1.35E–06	1.57E–06	4.45E–06	6.02E–06
<b>Reminder</b>						
A	1.53E–07	1.46E–07	2.99E–07	1.98E–08	5.93E–07	6.13E–07
B	3.81E–08	4.27E–07	4.65E–07	2.21E–07	1.73E–06	1.95E–06

**Table 5** (continued)

Organs/tissues	Neutron $W_R = W_R(E)$	Gamma $W_R = 1$	Total	Neutron $W_R = W_R(E)$	Gamma $W_R = 1$	Total
	Situation 1	Situation 2		Situation 1	Situation 2	
C	2.08E-06	3.72E-05	3.93E-05	5.83E-08	5.67E-07	6.25E-07
D	7.02E-06	7.02E-06	1.40E-05	1.90E-05	3.84E-05	5.74E-05

values are  $3.53 \mu\text{Sv/s}$  and  $8.87 \mu\text{Sv/s}$ ; (2) at point C in Situation 1, the bladder, with a dose of  $\sim 6.5 \text{ mSv/s}$ , has the highest value of  $H_T$ , whereas in Situation 2, the breast, with a value of  $\sim 3 \mu\text{Sv/s}$ , has the maximum value of  $H_T$ ; and (3) at point D for both situations, the skin has the maximum values of  $H_T$  ( $0.3 \mu\text{Sv/s}$  in Situation 1 and  $0.7 \mu\text{Sv/s}$  in Situation 2).

### 3.3. Whole body effective dose

Fig. 3 shows the contributions of each organ to the effective dose (i.e.,  $w_T H_T$ ) in Situations 1 and 2 at different positions. As can be seen, at positions A and B, breast and reminder have significant

contributions to the effective dose in both situations. In the case of position C, the bladder and breast have the maximum contributions to the effective dose in Situations 1 and 2, respectively. At position D, the reminder has the maximum value of  $H_T$  in both situations, with values of  $1.40 \times 10^{-5} \text{ Sv/s}$  and  $5.74 \times 10^{-5} \text{ Sv/s}$ , respectively.

The calculated whole body effective doses are presented in Table 6. As can be seen, the effective dose is highly dependent on the medical staff position. As expected, the presence of the patient in the medical room reduces the whole body effective dose of the medical staff in all positions. For example, at position C, the values of E are  $\sim 4.7 \text{ mSv/s}$  and  $1.56 \mu\text{Sv/s}$  in Situations 1 and 2, respectively, which indicates that the medical staff should not stand at this

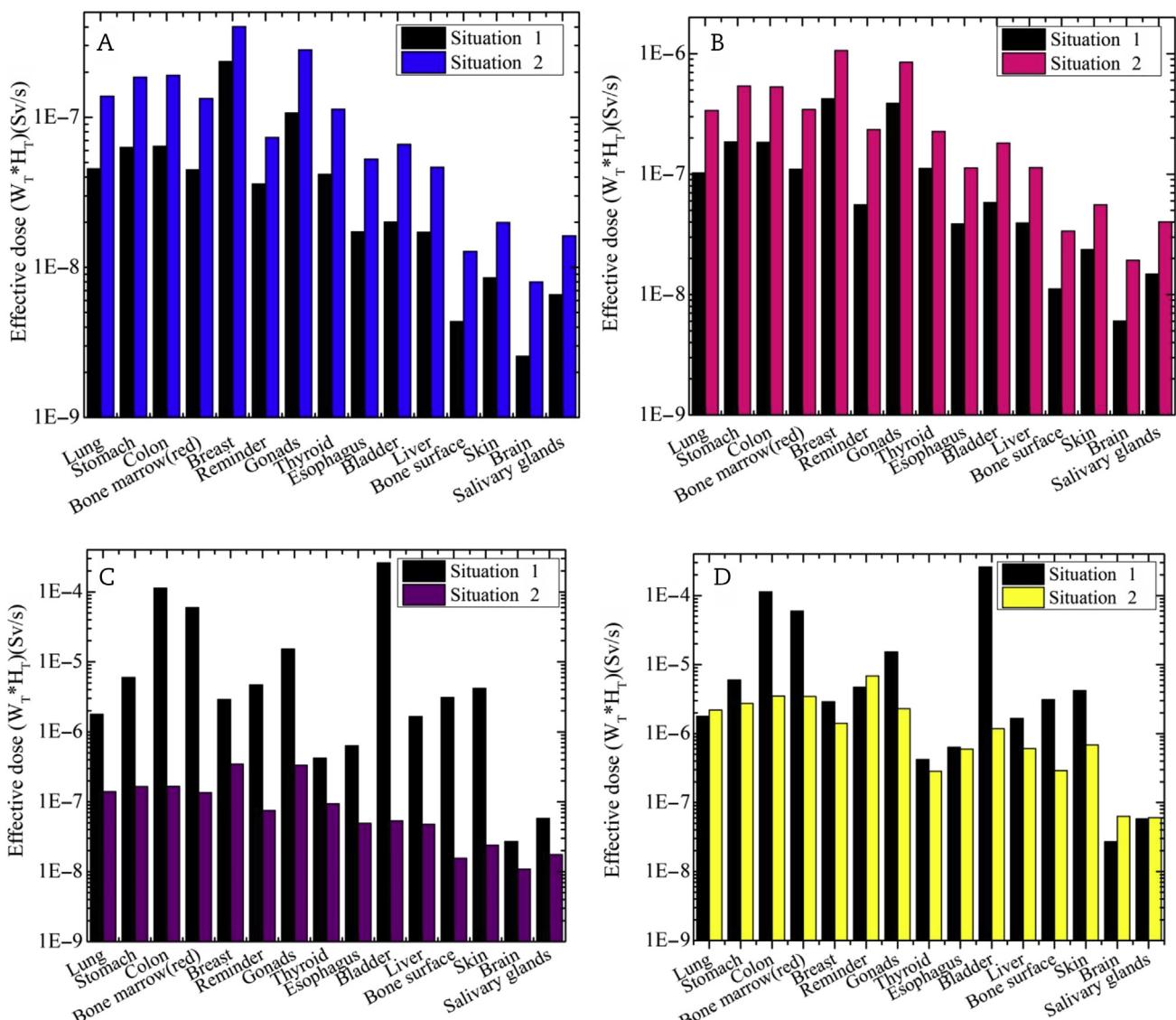


Fig. 3. Effective dose of organs in Situations 1 and 2 at different positions in medical room. (A) Near the door of the irradiation room. (B) At the center of the irradiation room. (C) At 200 cm from the beam port. (D) Close to the beam port on the left side of the patient.

**Table 6**

Whole body effective dose rate, E ( $\mu\text{Sv}/\text{s}$ ), for medical staff in Situations 1 and 2 at A, B, C, and D positions (see Fig. 1).

Position in the medical room	Situation 1	Situation 2
A	6.78	1.65
B	16.2	4.40
C	4,690	1.56
D	56.3	25.5

position in Situation 1.

The probability of the need for the presence of medical staff in emergency conditions in Situation 2 is high because the patient may need some help during the irradiation process. In this situation, the minimum and maximum values of E correspond to positions C and D, with values of  $1.56 \mu\text{Sv}/\text{s}$  and  $25.5 \mu\text{Sv}/\text{s}$ , respectively.

#### 4. Discussion

The results show that the medical staff effective dose is highly dependent on both the situation and the position. In Situation 1 at position C, the effective dose is  $\sim 4.7 \text{ mSv}/\text{s}$ , which indicates that this position should be considered a forbidden place, whereas the critical position in Situation 2, with a dose of  $\sim 25.5 \mu\text{Sv}/\text{s}$ , is position D.

#### 5. Conclusion

Using the MCNP4C Monte Carlo code and two ICRP 110 voxel based male phantoms, the medical staff effective dose during BNCT has been calculated in two situations and at different positions in the irradiation room. The obtained results reveal that the position and the situation of the medical staff play important roles in the absorbed dose of each organ. Furthermore, the presence of the patient will reduce the absorbed dose of the medical staff. The maximum medical staff effective dose in the presence of the patient is  $\sim 25.5 \mu\text{Sv}/\text{s}$ . These results show that, to develop BNCT treatment method as a type of routine cancer therapy, the radiation protection issue should be considered. As accelerator-based BNCT systems are designed for use in hospitals, controlled entry into the medical room should be taken into account because hospitals are generally assumed to be public and safe places.

It is clear that in emergency conditions in which the medical staff needs to be in the irradiation room during exposure, the use of personal protective equipment and the presence of several staff

members to assist the patient are necessary to reduce the effective dose. However, an automatic facility to move the patient bed out of the medical room in emergency conditions may be a useful approach to protecting the medical staff.

#### Conflicts of interest

The authors have no conflicts of interest to declare.

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