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Analysis on the emission and potential application of Cherenkov radiation in boron neutron capture therapy: A Monte Carlo simulation study

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HIGHLIGHTS

- Emission of Cherenkov photons in boron neutron capture therapy (BNCT) was explored.
- Cherenkov photons are generated from secondary charged particles of gamma in BNCT.
- Linear relation between boron concentration and Cherenkov photons was investigated.
- It presented the fundamental basis for applications of Cherenkov radiation in BNCT.

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ABSTRACT

This paper was aimed to explore the physics of Cherenkov radiation and its potential application in boron neutron capture therapy (BNCT). The Monte Carlo toolkit Geant4 was used to simulate the interaction between the epithermal neutron beam and the phantom containing boron-10. Results showed that Cherenkov photons can only be generated from secondary charged particles of gamma rays in BNCT, in which the 2.223 MeV prompt gamma rays are the main contributor. The number of Cherenkov photons per unit mass generated in the measurement region decreases linearly with the increase of boron concentration in both water and tissue phantom. The work presented the fundamental basis for applications of Cherenkov radiation in BNCT.

1. Introduction

Boron neutron capture therapy (BNCT) is a binary targeted radiotherapy based on thermal neutron capture reaction with ^{10}B (Chadha et al., 1998; Miyatake et al., 2005). This treatment modality is possible to release a significant dose to neoplastic cells during a single fraction of neutron exposure, with producing little harm to surrounding normal cells (Coderre et al., 2003; Hopewell et al., 2011). The development of accelerator-based boron neutron capture therapy (AB-BNCT) have made this technique available for hospital (Kreiner et al., 2007, 2013; Elshahat et al., 2007; Ceballos and Esposito, 2009; Suzuki et al., 2009). However, there is still technology lacking for the boron concentration measurement, which is used for quality assurance and control of BNCT to ensure that the boron concentration meets the treatment requirement.

Cherenkov radiation is a kind of optical light emitted when a charged particle travels at a speed greater than the phase velocity of light in the medium (Cherenkov, 1934). More recently, Cherenkov radiation has been explored as a tool of quality assurance in conventional x-ray radiotherapy (Glaser et al., 2014; Helo et al., 2014a). Researchers have demonstrated that the Cherenkov emission imaging may able to be used for radiotherapy dosimetry (Glaser et al., 2015; Shu et al., 2016a). Moreover, Cherenkov radiation imaging for surface dose visualization during breast radiation therapy and rapid optimization of clinical treatment geometry in total skin electron beam therapy were explored (Jarvis et al., 2014; Andreozzi et al., 2016). Jang et al. analyzed the physics of Cherenkov radiation generation during proton therapy to explore the potential application (Jang et al., 2012; Helo et al., 2014b). However, there is no research on the underlining physics and characteristics of Cherenkov radiation in BNCT for potential applications, *e.g.* boron concentration measurement.

In this paper, the physics of Cherenkov radiation during BNCT was discussed, by means of simulations. Based on the water phantom, we investigated the relationship between boron concentration and the number of Cherenkov photons per unit mass under different conditions of measurement region. For the possible practical application, we analyzed the relationship between boron concentration and the number of Cherenkov photons per unit mass in biological tissue.

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Table 1
Cherenkov threshold energies of electron and proton in water and tissue.

Material	Cherenkov threshold energy (MeV)	
	Electron	Proton
Water (Refractive index = 1.33)	0.2635	483.87
Tissue (Refractive index = 1.41)	0.2134	391.83

2. Materials and methods

2.1. Generation of Cherenkov radiation in BNCT

According to the theory of Cherenkov radiation, only charged particle can directly generate Cherenkov radiation. Therefore, Cherenkov radiation cannot be generated from primary neutrons in BNCT; however, it can be originated from the secondary charged particles. Secondary charged particles in BNCT include recoil nuclei generated by neutron elastic and inelastic scatter process, secondary electrons generated by interactions between recoil nuclei and medium, secondary electrons and positrons generated by secondary gamma rays from neutron capture reaction. Most of the recoil nuclei are protons, whereas others are heavy ions. Threshold energies of generating Cherenkov radiation from electron and proton in different materials are shown in Table 1. The energies of recoil nuclei are far lower than the Cherenkov threshold energy attributing to the usage of neutron beam (< 1 MeV) in BNCT. Considering that the secondary electrons of recoil nuclei do not have sufficient energy to emit Cherenkov photons (Shu et al., 2016b), the contributors for emitting Cherenkov photons are secondary charged particles from gamma rays generated by neutron capture reaction during BNCT. The general generation process of Cherenkov photons during BNCT is shown in Fig. 1.

2.2. Monte Carlo simulation

Geant4 Monte Carlo toolkit in version 4.10.01.p01 was employed to simulate the particle-transportation process. The prepackaged QGSP_BIC_HP combined with optical physics list was invoked in Geant4 to perform a coupled simulation for neutrons, charged particles, photons, and Cherenkov photons (Agostinelli et al., 2003; Allison et al., 2006). The QGSP_BIC_HP package includes standard EM physics list, high-precision neutron model for neutrons below 20 MeV, quark gluon string model, binary cascade model, pre-computed and various de-excitation models. The neutron cross-section library in Geant4 comes from the ENDF/B-VII database. The generation and optical transport of Cherenkov photons depends on the optical physics list.

The geometric and beam setup in Geant4 are illustrated in Fig. 2. A

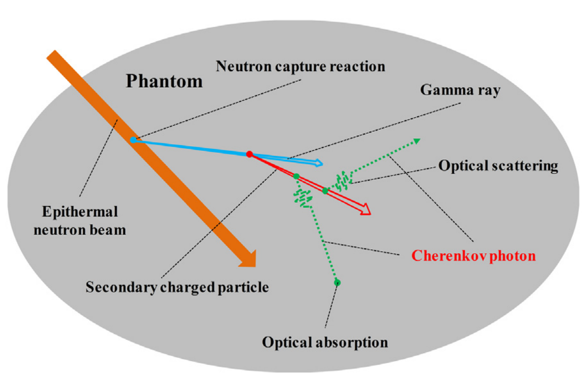

Fig. 1. Schematic of the generation of Cherenkov photons during BNCT. Different particles are plotted by different color, *i.e.* orange (neutron), blue (gamma), red (charged particle), green (Cherenkov photon) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

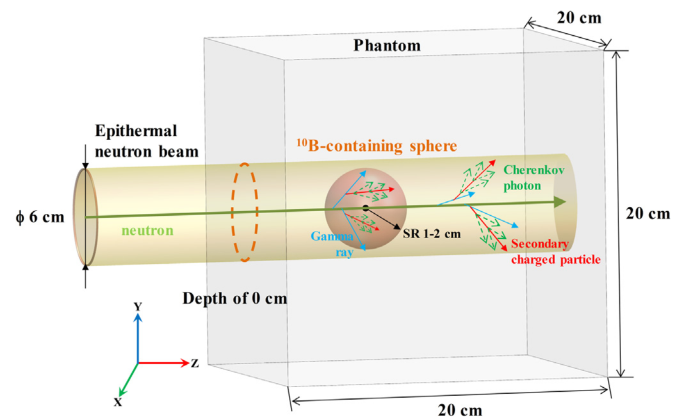

Fig. 2. Schematic of the geometry and beam setup in Geant4. The ^{10}B-containing sphere represents the measurement region. Lines of different colors present the generation process of Cherenkov photons.

20 cm × 20 cm × 20 cm water phantom was used in the simulation. A sphere containing ^{10}B was established in the center of the X-Y plane of the phantom. The ^{10}B-containing sphere was used to represent the measurement region. Measurement regions of different radii and depths were set to explore the relationship between boron concentration and Cherenkov photons under different conditions. It was set as a detector to score the quantities of interest. In this paper, the change rate of Cherenkov photons is defined as the variation of the number of Cherenkov photons per unit mass caused by the boron concentration change of 1 μg/g.

As a preliminary exploration, the setting of boron concentration distribution in the water phantom is an ideal situation. The boron concentrations in the sphere and the rest of the water phantom were assumed as 0–50 μg/g and 0 μg/g, respectively. To study the effect on biological tissues, the material of phantom replaced with soft tissue. The elemental composition of soft tissue is shown in Table 2. And the boron concentration distribution will be closer to the distribution in clinical trial case. The boron concentration of tumor/normal tissue ratio (T/N ratio) was set as 3.5. The boron concentrations in the sphere were assumed as 14–49 μg/g.

Epithermal neutron beam with a radius of 3 cm was employed to perpendicularly irradiate the phantom. The energy spectrum of the neutron beam was obtained from AB-BNCT, which is under construction by Neuboron Medtech Ltd. in China, as shown in Fig. 3 (Lee et al., 2014). All simulations were performed with 1.20×10^9 primary particles to keep the statistical uncertainty below 2% for the results in the measurement region.

3. Results and discussion

3.1. Water phantom

3.1.1. Dose and Cherenkov photons characteristics of epithermal neutron beam

The sphere with a radius of 1 cm was located at different depths to obtain the dose deposition by different particles and the generation of Cherenkov photons in the sphere. The boron concentration in ^{10}B-containing sphere was set as 30 μg/g to explore the characteristics of epithermal neutron beam. The results are shown in Fig. 4.

Boron dose and gamma dose reached the maximum values at depths

Table 2
Elemental composition of soft tissue.

Element	H	C	N	O	Na	P	S	Cl	K
Mass fraction (%)	10.5	25.6	2.7	60.2	0.1	0.2	0.3	0.2	0.2

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