Applied Radiation and Isotopes 124 (2017) 62–67

Contents lists available at ScienceDirect

Applied Radiation and Isotopes

journal homepage: www.elsevier.com/locate/apradiso

Optimization of the Compton camera for measuring prompt gamma rays in boron neutron capture therapy

Chun-hui Gong[a,b], Xiao-bin Tang[a,c,*], Di-yun Shu[a], Hai-yan Yu[a], Chang-ran Geng[a]

[a] Department of Nuclear Science and Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing, China
[b] National Institute of Nuclear Physics, INFN, Section of Pavia, Italy
[c] Collaborative Innovation Center of Radiation Medicine of Jiangsu Higher Education Institutions, Nanjing, China

ARTICLE INFO

Keywords:
Boron neutron capture therapy
Prompt gamma rays
Compton camera
Geant4

ABSTRACT

Optimization of the Compton camera for measuring prompt gamma rays (0.478 MeV) emitted during boron neutron capture therapy (BNCT) was performed with Geant4. The parameters of the Compton camera were determined as follows: 3 cm thick – 10 cm wide scatter detector (Silicon), 10 cm thick – 10 cm wide absorber detector (Germanium), and 1 cm distance between the scatter and absorber detectors. For a typical brain tumor treatment, the overall detection efficiency of the optimized Compton camera was approximately 0.1425% using the Snyder's head phantom with a sphere tumor (4 cm diameter and ~1 cm depth).

1. Introduction

Radiation therapy (RT) has been a valuable treatment method for cancer. The principle of RT is to deliver most of the doses to the tumor while minimizing the dose to the healthy tissues. As a special type of RT, BNCT (Bortolussi et al., 2014; Chao et al., 2016; Hang et al., 2016; Sauerwein, 2012) is considered as a binary radiotherapy that combines the targeting feature of a novel boron-containing material. Fig. 1 illustrates the process during BNCT. BNCT uses the nuclear capture reaction of the thermal neutron and ^{10}B. The secondary charged particles (α and ^{7}Li) have a finite range, which is on the cellular scale. Therefore, the radiation damage only occurs in the targeted cell.

However, one of the most important concerns of BNCT is determining the exact position of boron (i.e., the location of boron neutron capture reaction), and obtaining a real-time image of the location being treated has not been possible to-date. Therefore, new methods of obtaining an image of the treatment region are being developed. The characteristic prompt gamma rays emitted have been used to address this issue because they are emitted in-situ during the neutron capture interaction. Several researchers (Hales et al., 2014; Ishikawa et al., 2000; Kobayashi et al., 2000; Minsky et al., 2011; Murata et al., 2011; Rosenschöld et al., 2006; Verbakel and Stecher-Rasmussen, 2001; Yoon et al., 2014) recently began to investigate the use of the single-photon emission computed tomography (SPECT) imaging as a means of achieving the real-time image of the treatment region. However, SPECT cameras rely on two-dimensional (2D) collimation of the gamma rays to produce images, which limits their sensitivity and spatial resolution.

The Compton camera is a possible method for prompt gamma ray detection and overcomes the limitations of the SPECT imaging. The Compton camera localizes the position where the gamma ray is emitted by analyzing the kinematics of the Compton scattering. The Compton camera consists of at least two sensitive detectors, i.e., scatter detector and absorber detector, to score the position and energy loss of the Compton reaction. Several research groups (Lee et al., 2015; Stockhausen, 2012) proposed the application of the Compton camera for the measurement of the prompt gamma rays during BNCT. Stockhausen (2012) evaluated the feasibility of using the Compton camera in BNCT. However, to the best knowledge of the authors, no optimization study was found for the specific application. This fact limits the efficiency of the Compton camera in BNCT. Therefore, a study on the theoretical design of the Compton camera for its application in BNCT is required, i.e. optimizing its overall detection efficiency (i.e., effective counts) particularly for 0.478 MeV prompt gamma rays emitted during BNCT. The condition of the clinical BNCT environment for the Compton camera is complex and challenging in terms of neutron contamination, scatters, and algorithms for reconstruction (Peterson et al., 2010) and will be further researched in detail in future studies; thus, it is not in the scope of this current study.

The objective of this current study was to develop an optimal Compton camera specifically designed for measuring the characteristic prompt gamma rays emitted from the tissue during BNCT. The Compton camera geometry was optimized with Monte Carlo calculations. We basically used similar procedure as the Peterson study (Peterson et al., 2010), which was dedicated to prompt gamma camera design for

* Corresponding author at: Nanjing University of Aeronautics and Astronautics, China.
E-mail address: tangxiaobin@nuaa.edu.cn (X.-b. Tang).

http://dx.doi.org/10.1016/j.apradiso.2017.03.014
Received 7 November 2016; Received in revised form 23 February 2017; Accepted 17 March 2017
Available online 19 March 2017
0969-8043/

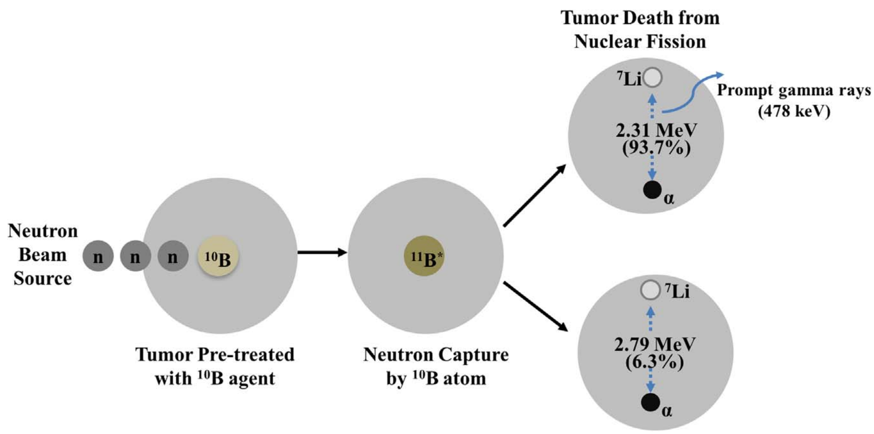

Fig. 1. Nuclear reactions of BNCT. The ^{10}B captures a neutron and then ^{11}B disintegrates in 93.7% into an α particle and an excited ^{7}Li nucleus, releasing a 0.478 MeV prompt gamma ray when it de-excited to its ground state.

proton therapy. The optimization was based on the optimal detection efficiency (i.e., effective count) of detectors with an isotropic gamma source. The thickness and the lateral width of the two detectors, i.e., one scatter detector and one absorber detector, as well as the distance between the two detectors, were determined by the effective counts of the Compton camera. Then, the neutron source was used to irradiate the Snyder's head phantom with a tumor, and the total number of prompt gamma rays detected was recorded in the Compton camera. These steps were performed to determine the feasibility of using the optimized Compton camera to measure the prompt gamma rays for BNCT and provided an overall detection efficiency in measuring prompt gamma rays emitted from the tissue during BNCT.

2. Materials and methods

2.1. Principle of a Compton camera

In a Compton camera system, the gamma rays emitted from a source placed in front of the scatter detector are scattered by electrons in the scatter detector, depositing a fraction of its energy before getting fully absorbed in the absorber detector. Under the circumstance where the deposited energies and interaction positions in both detectors are measured, the resulting angular distribution may be estimated by a cone with a central axis co-linear to the first and second interactions, and an angle, θ, computed from the following Compton equation:

$$cos\theta = 1 - m_e c^2 (1/E_2 - 1/E_\gamma) \tag{1}$$

where E_γ is the initial gamma energy, $m_e c^2$ is the electron rest energy, and E_1 and E_2 are the energies deposited at P_1 and P_2, respectively (Fig. 2). This event is denoted as a “true event”. The apex of the Compton cone is P_1, the axis of the cone is the line P_1P_2, and the half-angle of the cone is θ. The gamma ray emission points can be reconstructed by overlapping the cones from many interactions. The principle of the Compton camera is illustrated in Fig. 2.

2.2. Monte Carlo simulations

The simulations were performed with Geant4 toolkit (Geng et al., 2016; Guan et al., 2015; Wright, 2002), which is a Monte Carlo toolkit, composed of C+ + libraries. The *G4PenelopeComptonModel* was utilized to accurately simulate the Compton scattering process. The process implementation has been validated by several studies, and it has been validated with many external reference libraries (Cirrone et al., 2010; Weidenspointner et al., 2013). The Compton camera in this study was composed of a silicon detector (scatter detector) and a germanium detector (absorber detector). Silicon detector was sleeted for the potential for electron track Compton imaging (Thirolf et al., 2016),

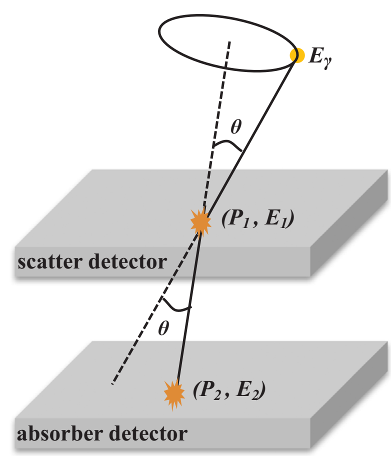

Fig. 2. The principle of the Compton camera. It consists of a scatter detector and an absorber detector. The Compton cone is constructed by the interaction positions and energies.

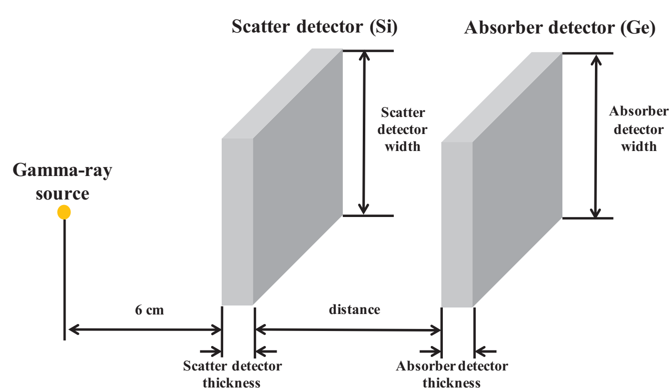

Fig. 3. The setup of the Geant4 simulation. A gamma point source is suited on the center axis of the Compton camera at a distance of 6 cm from the scatter detector.

which would increase the reconstruction efficiency. Germanium detector was chosen for its good energy resolution. The detectors, arranged in parallel-plane geometry, were modeled in Geant4 as shown in Fig. 3. An isotropic point source with an energy of 0.478 MeV was used in the Monte Carlo simulation to study the overall detection efficiency of the prompt gamma rays in BNCT. It was positioned at the center of the Compton camera field of view at a distance of 6 cm from the scatter detector. The thickness and lateral width of the two detectors, as well as the distance between the two detectors were studied as the variables for the optimization.