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Proton Linear Energy Transfer measurement using Emulsion Cloud Chamber

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ABSTRACT

This study proposes to determine the correlation between the Volume Pulse Height (VPH) measured by nuclear emulsion and Linear Energy Transfer (LET) calculated by Monte Carlo simulation based on Geant4. The nuclear emulsion was irradiated at the National Cancer Center (NCC) with a therapeutic proton beam and was installed at 5.2 m distance from the beam nozzle structure with various thicknesses of water-equivalent material (PMMA) blocks to position with specific positions along the Bragg curve. After the beam exposure and development of the emulsion films, the films were scanned by S-UTS developed in Nagoya University. The proton tracks in the scanned films were reconstructed using the 'NETSCAN' method. Through this procedure, the VPH can be derived from each reconstructed proton track at each position along the Bragg curve. The VPH value indicates the magnitude of energy loss in proton track. By comparison with the simulation results obtained using Geant4, we found the correlation between the LET calculated by Monte Carlo simulation and the VPH measured by the nuclear emulsion.

1. Introduction

Recently, the proton therapy becomes a major cancer treatment technique. Many sites throughout the world are in operation or are planned. The key advantage of proton therapy is its "Bragg curve"-based focus of the prescribed proton dose to the tumor region while sparing the surrounding normal tissue. This characteristic is a function of the energy loss of a proton as it passes through matter and interacts electromagnetically.

A primary proton track's energy loss per unit length in its cylindrical core, known as "Linear Energy Transfer (LET)", rapidly increases from the peak to the distal of the Bragg curve according to a depth-dose curve that represents the relation between the depth of the matter traversed and the energy loss [1,2].

In the radiobiological viewpoint, proton energy loss is delivered to both normal tissue and tumor. The energy thus imparted causes excitation of electron bonds in DNA material and the breakage of the DNA helical structure, thereby resulting in critical damage to the cell. Also a higher energy loss is more critical to the cell. This issue already has been discussed with respect to proton and carbon in the field of particle therapy.

One of classical techniques for the analysis of charged-particle tracks is "nuclear emulsion". This nuclear emulsion film can identify charged particles and this particle identification of ions is essential for the analysis of LET. Using the nuclear emulsion, the

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tracks of charged particles traveling on film can be obtained and analyzed with a microscope. The specific information of particles such as a track angle and a track stopping point and other data can be revealed by track reconstruction. Understanding the characteristics of charged particle tracks such as proton and carbon ion from this method has a significant advantage in clinical planning and radiobiological study. This method requires much manpower and hard work but the nuclear emulsion technique is cheaper and easier than a detector system with electronics. Recently, in the DONUT and OPERA experiments, this technique was rapidly developed. Especially the time consuming measurement of tracks by a manual scanning for nuclear emulsion was replaced by an automatic scanning system with track analysis software (NETSCAN) and high resolution film. This successful development has brought the field of emulsion to be applicable to many fields including elementary particle experiments [7–9,14].

The purpose of this study was to analyze the LET of a proton beam at specific positions on the Bragg curve in order to achieve a better understanding of proton therapy's precise radiobiological effectiveness. To that end, the proton beam's LET was calculated by using Geant4-based Monte Carlo simulation of a proton therapy machine and a nuclear emulsion. The relationship between this calculation result and the results of a nuclear-emulsion-based track analysis of the proton beam was derived. For beam exposure, a commercial clinic machine, IBA Proteus235 operated at National Cancer Center at Republic of Korea, was used. In a previous study, a simulation application that consists of the modeling and validation of the proton therapy machine was proposed [3,4]. This application was used for the development of a new simulation application in this study. The newly developed application includes the structure of the Emulsion Cloud Chamber (ECC) in order to simulate nuclear emulsions.

2. Materials and methods

2.1. Nuclear emulsion

In this study, the nuclear emulsion named "OPERA emulsion", recently developed for the OPERA experiment by Nagoya University and the Fuji Photo Film Co., Ltd., was used [5]. It is of high quality, the thickness is uniform as well as radiation sensitivity over the entire area. Due to these advantages, the nuclear emulsion is suitable for data collection and processing using an optical microscope. Fig. 1 depicts a schematic diagram of an ECC including five emulsion plates. An emulsion plate consists of two emulsion layers and a plastic base. The thickness of an emulsion layer is 44 μm and the thickness of a plastic base (TAC, Triacetate) is 205 μm. Emulsion layers are formed on both sides of the plastic base. Each layer is composed of silver (silver halides) microcrystalline emulsion gel constituted of C, N, O, Ag and Br and having a fine grain size of approximately 0.1 μm. Its density is 2.71 g/cm^3 and the mass composition is provided in [6]. Also the density of Triacetate is 1.28 g/cm^3 and the mass composition is given in [6].

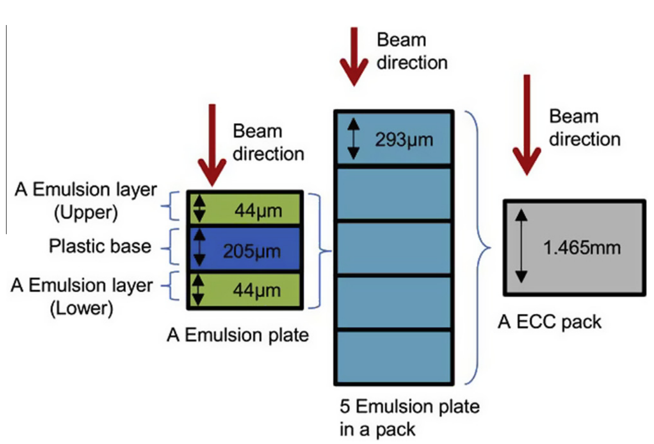

Fig. 1. Schematic drawing of ECC. An ECC pack was made up of five emulsion plates. A plate has a plastic base and two emulsion layers on each side of base.

Super-Ultra Track Selector (S-UTS), the latest automatic scanning system, is utilized for scanning tracks using the nuclear emulsion. In order to capture tracks, S-UTS captures 16 sliced-images from an emulsion layer. These images are scanned by increasing the optical focal depth of the microscope with CCD camera along the beam direction [7,8]. Track segments from 16 images per emulsion layer can be obtained by a track recognition algorithm [7,9].

For the track reconstruction, NETSCAN, the three-dimensional track reconstruction software developed by Nagoya University, is utilized [10]. This software connects track segments per emulsion layer. After finishing this process in all layers of ECC, the software connects tracks between two layers where two emulsion plates are met. Finally, the software reconstructs the whole trajectories of tracks by connecting tracks of all plates of ECC. Once tracks have been reconstructed, the grain density per track can be acquired from pixels' value (pixel size: 0.29 μm × 0.23 μm) that is located along a track line and is captured by the scanning system's CCD camera.

Pulse Height (PH) and Volume Pulse Height (VPH) were evaluated from the grain density of track in emulsion. The grain density was approximately proportional to the energy loss of charged particle [14]. The PH is the number of footprints in 32 images touching the sides of the two emulsion layers between two emulsion plates and was determined knowing whether the footprint exists or not in each images. Because of technical limitation, the maximum PH is 32. The PH values indicate whether a particle has sufficient energy to penetrate the TAC between two sides of two emulsion layers in an emulsion plate. The VPH value is defined by the sum of the number of pixels relative to the grain density of a track which has several track segments with 16 images per emulsion layer. Notably, because of ionization process, a charged particle maintains a thicker width of track [11–13]. Therefore, the VPH value indicates the energy deposition of a particle by ionization during its passage through nuclear emulsion [14].

2.2. Equipment and experimental setup

The National Cancer Center (NCC) in South Korea operates the IBA Proteus235 system, which includes a cyclotron, a beam transport line, three universal nozzle machines installed in two gantry rooms and one horizontal fixed beam line room [15]. The experiment used a proton beam with Bragg peak range of 13.89 cm (corresponding to an energy of 150 MeV) in the horizontal fixed beam nozzle room. The beam current was limited to 10% of that used under normal clinical conditions. An ECC pack consisting of 5 emulsion plates with a vacuum sealing pack covered by the aluminum laminated paper was installed at 5.2 m distance from the edge of the aperture in the nozzle structure. The limitation of beam current and distance was required in order to avoid the overlapping of proton tracks in an emulsion layer [14]. In order to reconstruct proton tracks without the overlapping, the automatic scanning system was limited to the track density of 10^6 protons on a 10 × 10 cm^2 (100 protons/mm^2). This condition was considered originally for rare event detection such as in OPERA experiment. For our experiment, the track density was limited to 10^4 protons reaching the PMMA phantom. Because the emulsion plate surface area was 2.5 cm × 2.5 cm, and the thickness was 44 μm, a small surface area was considered in order to reduce the S-UTS scanning time.