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Evaluation of the distribution of activation inside a compact medical cyclotron

Toshioh Fujibuchi[a,*,1], Takatoshi Toyoda[b,1], Shingo Baba[c], Yoshiyuki Umezu[d], Isao Komiya[d], Masayuki Sasaki[a], Hiroshi Honda[c]

[a] Department of Health Sciences, Graduate School of Medical Sciences, Kyushu University, Japan
[b] Department of Health Sciences, Faculty of Medical Sciences, Kyushu University, Japan
[c] Department of Clinical Radiology, Graduate School of Medical Sciences, Kyushu University, Japan
[d] Division of Radiology, Department of Medical Technology, Kyushu University Hospital, Japan

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ABSTRACT

The distribution of activation inside a compact medical cyclotron was evaluated by measuring 1 cm dose equivalent rates and γ-ray spectra. Analysis of the distribution of activation showed high activation at the deflector and the magnetic channel. Radionuclides ^{60}Co, ^{57}Co, ^{65}Zn, and ^{54}Mn were detected. Different radionuclides were generated from different components of the cyclotron, and low-activity radionuclides could be detected under low-background-radiation conditions.

1. Introduction

Positron-emitting isotopes that have a short half-life, such as ^{18}F and ^{11}C, are used in positron emission tomography (PET). In particular, ^{18}F is used to synthesize ^{18}F-fluorodeoxyglucose (^{18}F-FDG). PET examinations have been covered by public insurance in Japan since 2002. Thus, the number of hospitals that use compact medical cyclotrons to produce positron-emitting isotopes has increased so that 149 cyclotrons were in operation at medical facilities in Japan in 2015 (Japan Isotope Association, 2015).

A compact medical cyclotron creates radionuclides for PET by bombarding a target with cyclotron-accelerated charged particles. Nuclear reactions, such as $^{18}O(p,n)^{18}F$, that occur in the cyclotron lead to secondary neutrons (Guimaraes et al., 2012). The neutrons penetrate many types of materials and easily cause activation, including of the cyclotron itself and the concrete wall of the cyclotron vault room (Fujibuchi et al., 2009).

When cyclotron facilities are decommissioned in Japan, the activated materials, including the entire cyclotron facility, must be treated as radioactive waste and discarded. Thus, the cost of decommissioning may place a severe burden on the hospital (IAEA, 2003; Ishimoto et al., 2005). The number of decommissioned cyclotrons will increase rapidly in the near future. Therefore, it is important to have a better understanding of the conditions in which the cyclotron and the cyclotron room undergo activation. This knowledge will help determine the distribution of activation inside the cyclotron and the cyclotron vault room and reduce the time and cost associated with decommissioning.

In this study, the distribution of activation inside the acceleration field of the cyclotron was measured using phosphor plates, and the 1 cm dose equivalent rate inside the cyclotron was measured using a CsI(Tl) scintillation detector. The latter was performed for the sake of the workers engaged in decommissioning the cyclotron. On the basis of the results from these measurements, we obtained γ-ray spectra at particular points in the acceleration field using a CdZnTe semiconductor detector to determine the radionuclides generated by activation. Using metal samples collected from the yoke, a high-purity Ge detector determined the nuclides generated inside the yoke by activation.

2. Material and methods

2.1. Cyclotron

The subject of the present study was a BC1710 cyclotron (Japan Steel Works, Ltd., Muroran, Hokkaido, Japan) due to be decommissioned by Kyushu University Hospital. This cyclotron accelerated protons to a maximum energy of 17 MeV and deuterons to a maximum energy of 10 MeV. The average beam intensity during operation was 20.7 μA; a deflector was used for beam extraction. The cyclotron had been in operation for 27 years and had a cooling time of 6 years.

* Corresponding author.
E-mail address: fujibuch@hs.med.kyushu-u.ac.jp (T. Fujibuchi).
[1] These authors contributed equally to this work.

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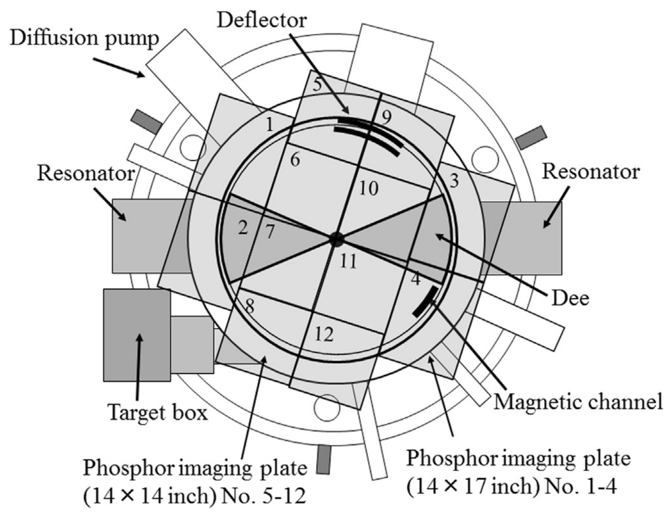

Fig. 1. Position of the magnetic channel, deflector, target box, diffusion pump, resonator, dee and phosphor imaging plates.

2.2. Measurement of the distribution of activation inside the acceleration field

Phosphor imaging plates ST-VN ST-VA (14 × 14 in., Fujifilm) and ST-VI (17 × 14 in., Fujifilm) were placed in the acceleration field to detect emitted γ-ray from activation that had occurred inside the cyclotron. Because the intensity of activation depended on the location in the cyclotron, the phosphor imaging plates recorded the distribution of activation. Fig. 1. shows the position of the phosphor imaging plates. Because the phosphor imaging plates had a low sensitivity to γ-ray, they remained in the cyclotron for 70 h to measure the γ-ray emitted by acceleration field. The phosphor imaging plates were then scanned and the pixels were converted into relative dose via the ImageJ software program. The relationship between pixels and dose is given by (Fujibuchi et al., 2014)

$$y = \exp\left(\frac{x-490.105}{114.32}\right) \quad (1)$$

where y is the relative dose and x is the pixel value. The relative dose was converted to an 8-bit gray-scale image. These data were obtained before the experiment.

2.3. Measurement of the 1 cm dose equivalent rate around the acceleration field

A CsI(Tl) scintillation detector (C12137, Hamamatsu Photonics, Hamamatsu City, Shizuoka, Japan) was used to measure the 1 cm dose equivalent rate to determine the dose rate around the acceleration field. Fig. 2. shows the measurement points set along lines radiating out from the center of the cyclotron. The angle intervals were set at 30°, 0° for the magnetic channel. The distance from the center of the cyclotron (0 cm) to the measurement points was 15, 30, 45, 65, and 85 cm. The CsI(Tl) scintillation detector was placed on styrene foam and shielded by a 5-cm-thick lead block, the purpose of which was to avoid detecting γ-rays from the other parts of the cyclotron and improve the directivity of the detector.

To perform the measurements at the 0, 30, 45, and 65 cm positions, a long board was placed across the cyclotron accelerator (see Fig. 3) and the shielded detector was set in a small cart placed on the board. The board and the cart were moved to each measurement position. The setup of measurement point was calibrated using marks on the acceleration field. The angles of the measurement points were calibrated by setting the board along the marks in Fig. 2. The measurement positions were calibrated by measuring the distance from the center of the cyclotron. For the measurement at 85 cm, the shielded detector was set directly on the cyclotron field. The setup for taking the measurements is shown in Fig. 3.

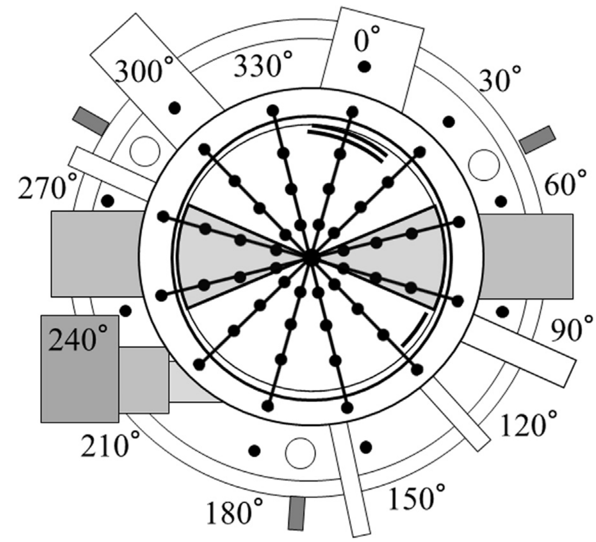

Fig. 2. Black dots indicate the points at which the 1 cm dose equivalent rate was measured.

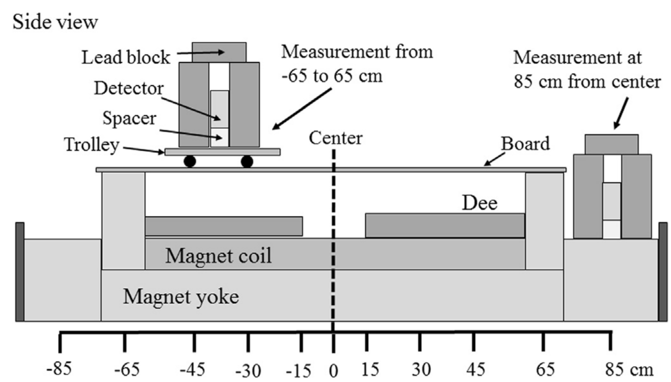

Fig. 3. Schematic illustration of the setup for measuring the 1 cm dose equivalent rate.

2.4. In situ γ-ray spectrometry inside the acceleration field

The CsI(Tl) scintillation detector and a CdZnTe semiconductor detector (GR-1, Kromek Group plc, Sedgefield, UK) were used to obtain the γ-ray spectra to determine the radionuclides generated by activation inside the acceleration field. The measurement points included those determined using the results of the 1 cm dose equivalent rate measurements, plus the hole to the target box (see Fig. 4.). The CdZnTe detector was shielded by 5-cm-thick lead blocks for the measurements at points a and d and by 1-cm-thick lead blocks for the measurements at points b and c. The CsI(Tl) scintillation detector was used at point e. In addition, five metal cores from inside the cyclotron yoke were sampled: positions f, g, h, and i were around the acceleration field and position j was inside the acceleration field. The metal cores were crushed, filled with U8 containers, and then weighed. The γ-rays from each of the metal cores were measured for 3600 s using a high-purity Ge detector (model 35190, ORTEC, Advanced Measurement Technology, Oak Ridge, TN, USA). The radionuclides were determined and their activity was calculated from the γ-ray spectra.