Measurement of Neutron Flux in a Medical Compact cyclotron room with Boron-Containing water Self-Shielding

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The spread of PET has caused a surge in the number of compact medical cyclotrons used for production of radiopharmaceuticals. Some cyclotrons have a self-shield, and the presence of self-shielding greatly reduces the neutron flux discharged into the room housing a cyclotron. The neutron fluxes in a cyclotron room with and without a self-shield were evaluated. The thermal neutron flux outside a cyclotron without a self-shield was about 10^5 cm^{-2} s^{-1}, whereas that with a self-shield was about 10^2 cm^{-2} s^{-1}.The radioactivity of the wall of a self-shield type cyclotron falls below the clearance level. For ascertaining the radiation safety of the public and of workers, safe management of radioactive waste is critical for successful operation and decommissioning of accelerator facilities.

Keywords: medical compact cyclotron, positron emission tomography, radioactivation, neutron, decommissioning,

1. Introduction

Positron emission tomography (PET) is widely employed in many countries as a standard and noninvasive analysis technique for determining the location and concentration of physiologically active components in the human's body. The spread of PET has caused a surge in the number of compact medical cyclotrons used for production of radiopharmaceuticals. The rapid growth of PET as a clinical tool has led to a rapid increase in the number of dedicated PET radiopharmaceutical production sites. (*p*, *n*) reactions are generated by bombarding of suitable target nuclides with high-energy particle beams that are guided from a medical cyclotron. The secondary neutron field induced by reactions among charged particles contributes to the radioactivation of cyclotron materials, and it may additionally activate the shielding structures. During the operation of a cyclotron, radioactive nuclides with comparatively long half-lives are produced by the accelerated particles and neutrons are secondarily deposited in the accelerator in areas such as target foils, cooling water, and concrete[1)]. It is the responsibility of the hospital or medical institute to protect workers, the public, and the environment from the hazards posed by radioactive waste during decommissioning. Decommissioning of a medical cyclotron is thus an onerous task for a hospital[2].

In this study, we compared the neutron fluxes in cyclotron rooms with a boron water type self-shield and without a self-shield. The activation of material in a cyclotron room was evaluated, and the decrease of activation with the self-shield was confirmed.

2. Materials and Methods

2-1 Equipment

In this study, we used a CYPRIS HM-18 cyclotron (Sumitomo Heavy Industries, Ltd, Niihama, Japan) and a PETtrace (GE Healthcare, Milwaukee, WI) as cyclotrons without and with self-shields, respectively. Each cyclotron produces only ^{18}F by an [^{18}O] H_2O (p, n) ^{18}F reaction. The HM-18 was operated for 60 min per day about four times a week at an average beam current of 20 μA and proton beam acceleration energy of 18 MeV. This cyclotron produces about 50 GBq of 18F a day. The PETtrace was operated for 70 min per day about six times a week at an average beam current of 40 μA and proton beam acceleration energy of 16.5 MeV. This cyclotron produces about 100 GBq of ^{18}F a day. These cyclotrons are fixed-energy isochronous cyclotrons that accelerate negatively charged hydrogen ions as protons (H^-).

2-2 Measurement of thermal neutrons by use of gold foils in the cyclotron room

Neutron flux is often evaluated by neutron activation analysis that measures the radioactivity induced in a sample foil by an (n, γ) reaction. Gold foils and a germanium semiconductor detector are typically used for these measurements[3]. Gold foils (1 cm φ × 0.05 mm thick; weight: 68 mg) were positioned on the floors of the cyclotron rooms at intervals of 50 cm from the target, and they were used for measurement of the neutron flux. The ratio of the thermal neutrons to fast neutrons was evaluated by covering of a gold foil with a 1-mm-thick layer of cadmium. The radioactivity of a single gold foil was measured with a high-purity germanium detector (GEM-50, Ortec), while those of other samples were evaluated relatively with use of an imaging plate[4]. Figure 1 and 2 show the arrangements of the HM-18 and PETtrace cyclotron rooms, respectively; their concrete walls were about 1.5 and 0.5 m thick, respectively. Gold foils were arranged from the floor to a height of 1 m and 0 m, respectively (from 1a to 12a and 1b to 12b in Fig 1and 2).

In addition, gold foils were arranged from point A to point K on the floor. Because the device might break down, cadmium could not able to be arranged under the self-shield (points B, C, D, H, and I).

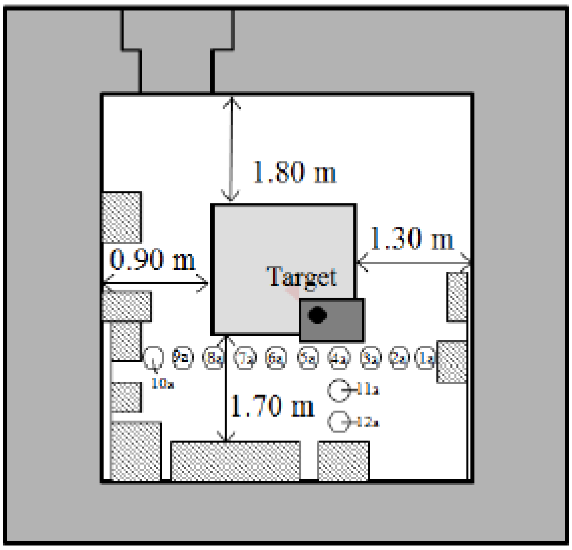

Figure 1. Arrangement of glass dosimeter and gold foils in the HM-18 cyclotron room.

2-3 Long term neutron measurement with use of PADC in a self-shielded cyclotron room

The neutron dosimeter made of poly allyl diglycol carbonate (PADC, commercially called "CR-39") plastic[5] fabricated by Nagase-Landauer Co., Ltd., was used for measurement of neutrons. The neutron dosimeter by Nagase-Landauer has a size of 1.0×2.0 cm^2. PADCs were attached to the wall of the PETtrace cyclotron room for one month, and the thermal and fast neutron doses were evaluated. These dosimeters were used with a polyethylene radiator for increase in the selectivity of fast neutrons and with a boron nitride converter for enhancement of the selectivity of thermal neutrons[6].

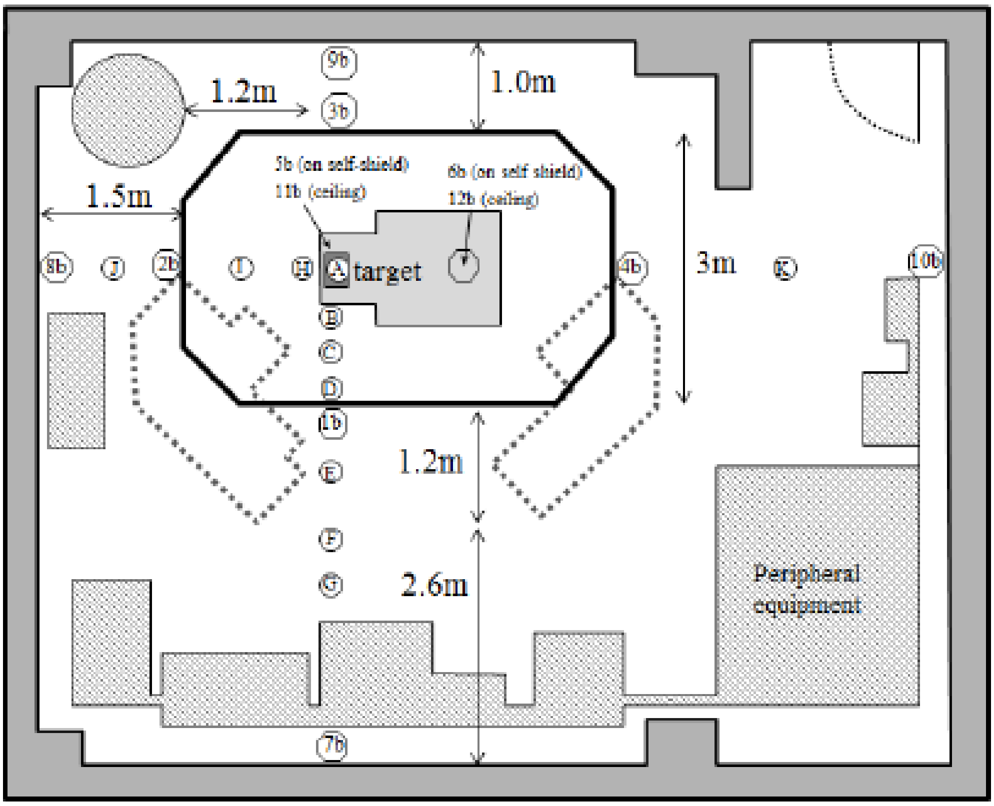

Figure2. Arrangement of glass dosimeter and gold foils in the PETtrace cyclotron room.

3. Results

3-1 Measurement of thermal neutrons on the floor of the cyclotron room

Table 1 lists the thermal neutron fluxes and the Cd ratios in the cyclotron rooms. The measurements gave average thermal neutron fluxes of about 10^5 and 10^2 cm^{-2} s^{-1} for HM-18 and PETtrace, respectively. The average Cd ratios were about 2.7 and 1.2 for the HM-18 and PETtrace, respectively. The thermal neutron flux had decreased by three digits outside the self-shield.

3-2Long term neutron measurement by use of PADC in a self-shielded cyclotron room

The neutron dose measured by PADC in the PETtrace cyclotron room is shown Table 2. The doses of the thermal neutron were low compared with these of the fast neutrons.

4.Discussion

Table 1 shows that the thermal neutron flux was reduced by three orders of magnitude lower when a self-shield was installed. A similar tendency was observed in other studies[7–15]. The clearance level (RS-G-1.7)[16] is 0.1 Bq/g for ^{60}Co, ^{152}Eu, and ^{134}Cs. The neutron fluxes for ^{60}Co, ^{134}Cs, and ^{152}Eu (which are the principal activation nuclides generated in concrete) are such that $\Sigma D/C$ becomes unity for typical cyclotron usage (1 h per day for 30 years). The composition of concrete was calculated and the neutron flux was found to be about 2.7×10^{3}cm^{-2}s^{-1}. The neutron flux attenuated behind the self-shield and was about 102cm–2s–1when the cyclotron was operating. Therefore, the radiation level of the walls was sufficiently below the clearance level. However, the self-shield contains holes that connect with the exterior, and neutrons may pass through them. It is thus necessary to monitor the neutron leakage at each facility. It is essential to stop any leakage as soon as it occurs. Moreover, the floor should be corresponding as a no-self-shield type.

During cyclotron decommissioning, the amount of radioactive nuclides at a cyclotron facility must be evaluated. The amount of induced radioactivity can be predicted by estimation of the amount of secondary neutrons from the operational conditions. Adequate specifications for radioactive waste based on scientific data, the type of cyclotron, and its operational conditions are essential for safe decommissioning.

Table 1 Thermal neutron fluxes and Cd ratios of cyclotron room measured by gold foils.

Point (Fig.)	HM-18 Cd ratio	HM-18 Thermal neutron flux ($\times 10^{5}$ $cm^{-2}s^{-1}$)	Point (Fig.)	Height from floor (m)	PETtrace Cd ratio	PETtrace Thermal neutron flux ($\times 10^{1}$ $cm^{-2}s^{-1}$)
1a	2.7	5.7 ± 1.3	1b	1	1.2	3.5 ± 0.8
2a	2.3	8 ± 1.8		0	1.1	4.6 ± 1.0
3a	2.6	11.7 ± 2.5	2b	1	1	3.5 ± 0.7
4a	2.3	16.6 ± 3.7		0	1.3	3.7 ± 0.8
5a	2.2	14.9 ± 3.3	3b	1	1.1	4.1 ±0.9
6a	2.7	11.4 ± 2.5		0	1.2	4.7 ± 1.0
7a	2.5	6.1 ± 1.3	4b	1	1.5	3.1 ± 0.7
8a	1.7	0.9 ± 0.2		0	1.4	4.8 ± 1.1
9a	1.9	1 ± 0.2	5b	on self-shield	1	16.0 ± 3.5
10a	2.2	0.5 ± 0.1	6b	on self-shield	1	1.9 ± 0.4
11a	3.1	1.8 ± 0.4	7b	1	1.1	1.6 ± 0.4
12a	2.1	1.4 ± 0.3		0	1	4.4 ± 1.0
			8b	1	1.2	6.7 ± 1.5
				0	1.3	7.8 ± 1.7
			9b	1	1.2	2.3 ± 0.5
				0	1.2	4.1 ± 0.9
			10b	1	1.1	9.6 ± 2.1
				0	1	7.8 ± 1.7
			11b	Ceiling	1.1	8.9 ± 2.0
			12b	Ceiling	1.1	6.6 ± 1.5

Table 2Neutron dose for 1 month in cyclotron room using PADC.

Point (Fig.)	Height from floor (m)	Thermal neutrons (mSv)	Fast neutrons (mSv)
1b	1	0.001	0.010
	0	0.002	0.050
2b	1	0.001	0.060
	0	0.003	0.040
3b	1	0.000	0.000
	0	0.001	0.000
4b	1	0.000	0.000
	0	0.002	0.000
5b	on self-shield	0.002	0.070
6b	on self-shield	0.001	0.000
7b	1	0.000	0.000
	0	0.000	0.010
8b	1	0.002	0.020
	0	0.022	0.080
9b	1	0.001	0.010
	0	0.000	0.010
10b	1	0.003	0.000
	0	0.001	0.000
11b	Ceiling	0.006	0.090
12b	Ceiling	0.000	0.000

5.Conclusions

The neutron flux in a cyclotron laboratory with a self-shield was evaluated. The thermal neutron flux outside the self-shield was about 10^2 cm^{-2} s^{-1}, and the radioactivity of the wall of a self-shield cyclotron was below the clearance level. Due to the increasing public awareness of the problem, safe management of radioactive waste is critical for successful operation and decommissioning of accelerator facilities.

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