ORIGINAL

The impact of self-shielded cyclotron operation on small-animal PET/CT equipment installed nearby, on the floor just above

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Abstract : Purpose : The purpose of this study was to evaluate the impact of a cyclotron on small-animal PET equipment installed directly above the cyclotron. Methods : The cyclotron equipment was HM-12, which has two targets, and the PET/CT equipment was Inveon. The equipment was installed in conformity to Japanese law and regulations. Before installation of the PET/CT equipment, the radiation dose, radio waves, and static and fluctuating magnetic fields were measured at the position where it would be placed, both when the cyclotron was in use and when it was not in use. After installation of the PET/CT, natural background and emission counts were measured at the same place under the same conditions. Results : An increase of radiation dose was observed when the target nearest the PET equipment was used. There were no distinct effects of radio waves or static and fluctuating magnetic fields. A significant increase of emission counts, approximately 300 cpm, was observed when the nearest target was used. Conclusions : Though radio waves and static and fluctuating magnetic fields generated by running cyclotron had no influence, a significant increase in emission count was observed. Careful attention should be paid to this influence when very low-radioactivity PET measurements are done. J. Med. Invest. 61 : 46-52, February, 2014

Keywords **:** *self-shielded cyclotron, PET/CT for small animals, radiation dose, magnetic field*

INTRODUCTION

Molecular imaging, which evaluates the function of molecules using medical imaging techniques *in vivo*, is becoming widespread in both basic and clinical research (1, 2). The combined equipment of positron emission tomography (PET) and x-ray computed tomography (CT), called PET/CT, is one of the modalities used for molecular imaging research. It has numerous benefits in comparison to other modalities such as magnetic resonance imaging (MRI), single photon emission computed tomography (SPECT) and ultrasound (3). Because of the use of high-energy gamma-ray emitted radio isotopes, it combines high sensitivity and a high quantitative ability to evaluate the biological functions of both human and animals (4, 5). Since the half-lives of the radio isotopes such as ^{11}C, ^{13}N, ^{15}O and ^{18}F that are used for PET are very short in comparison to the other radio isotopes that are used for SPECT, it is desirable that the physical distance between PET equipment and the cyclotron that

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produces the radio isotopes for PET be as short as possible to reduce the delivery time. When using the radio isotopes that have very short half-lives such as ^{11}C, ^{13}N and ^{15}O, there is the possibility that PET scan is performed on the situation of running cyclotron. However, the radiation, radio waves, static and fluctuating magnetic fields that are generated by a running cyclotron may influence the data of PET if it is installed in close proximity to the cyclotron room. The purpose of this study was to evaluate the impact of cyclotron operation on the readings from small-animal PET equipment installed directly above the cyclotron.

MATERIALS AND METHODS

The cyclotron was an HM-12 (Sumitomo Heavy Industry, Kawanoe, Japan). This cyclotron is able to employ proton and deuteron beams with maximum energies of 12 MeV and 6 MeV, respectively ; the maximum beam current is 100 μA. There are two targets in this cyclotron and their heights are 600 mm (target A) and 1,200 mm (target B). The direction of the beam is upward to target A and downward to target B. This cyclotron has as its self-shielding protective layers of 25-mm-thick polyethylene, 4.55-mm-thick lead, 1.65-mm-thick steel and 53.8-mm-thick heavy concrete. The PET/CT equipment was Inveon (Siemens Health Care, Knoxville, TN) that is for small animals. Its crystal is lutetium oxyorthosilicate (LSO) with a total array of 25,600 elements $1.51 \times 1.51 \times 10$ mm^3 in size. Their configuration is shown in Figure 1. The cyclotron equipment was installed on the first floor and the PET/CT equipment was installed on the second floor directly above the cyclotron equipment. The ceiling height of the cyclotron room was 4,370 mm and the ceiling thickness (including the floor thickness of the PET/CT room) was 300 mm of concrete. The distances between the two targets of cyclotron and the center of the detector ring of the PET/CT equipment were 3,800 mm (target A) and 3,330 mm (target B).

Evaluation before the installation of PET/CT equipment

Gamma-ray spectrum and radiation dose rate, leakage of radio waves, and static and fluctuating magnetic fields were evaluated before the installation of PET/CT equipment. All measurements were done in the room for PET/CT equipment. The gamma-ray spectrum was measured using an NaI spectrometer (ORTEC digiBASE-E ; AMETEK, TN, USA) and an ionization survey meter (450P-DE-SI ; Victoreen Instruments Co., OH, USA) was adapted to measure the dose rate of gamma rays. Leakage of radio waves was measured using a spectrum analyzer (E4401B, Agilent Technologies, CA, USA) with bi-conical antenna (BBA9106, Shuwarzbeck-Mess Electronik OHG, Hidelberg, Germany) that was set at 1 m above the floor. The measurement frequency of the leakage of radio waves was 45 MHz, and the maximum value for a five-minute period was found repeatedly during the running of the cyclotron. The static magnetic field was measured using MM-340 (MTI Corporation, CA, USA) and the fluctuating magnetic field was measured using SRA-1610 with Mag-07 (Bartington Instruments, England). The magnitude of the magnetic field along x, y and z directions was measured and resultant value was calculated from the sum of their sum of squares. Their sensors were set to 300 mm above the floor.

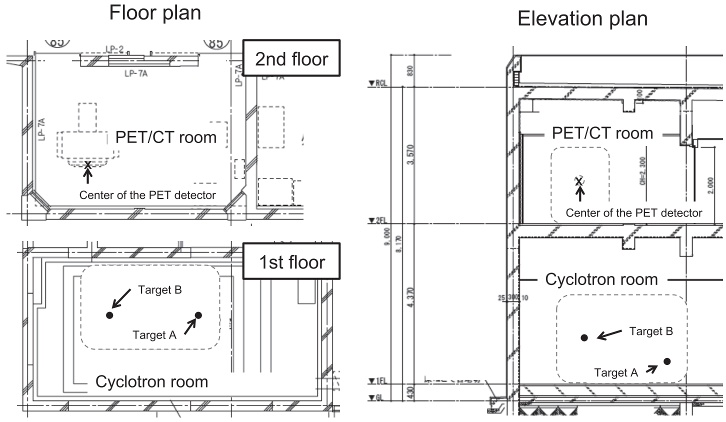

Figure 1 : Blueprint of our PET/CT facility. The PET/CT equipment was installed directly above the cyclotron. Locations of the two targets and the center of the PET detector were marked by dots and x, respectively.

Evaluation after the installation of PET/CT equipment

All measurements after the installation of PET/CT equipment were done using PET/CT equipment itself. The natural background of the crystal and the background of the emission mode were measured in this evaluation. The natural background of the crystal was measured using the emission mode within the seven 100-keV energy ranges between 50 keV and 750 keV (50-150 keV, 150-250 keV,..., 650-750 keV). The timing window was 3.432 ns, the measurement time was 5 minutes on a running cyclotron with target A (on-A), with target B (on-B) and on an idle cyclotron (off). Each measurement was repeated 4 times afterward, for a total of five measurements for the on-A, on-B, and off settings. To evaluate the influence on PET/CT measurement, the background of emission mode was measured with the energy range from 350 keV to 650 keV, with a timing window of 3.432 ns, and a 40-min measurement time.

Statistical analyses

R software ver. 2.8.1 was used for all statistical analyses. ANOVA was applied to test statistical differences between each energy window range. The normality of acquired data was initially estimated by the Shapiro-Wilk test. If normality was found, Levene's test was used to test for equality of variance. If the p value of Levene's test was ≥ 0.05, ANOVA was chosen to test significant differences between groups. If the ANOVA p value was less than 0.05, significant differences were assessed by Tukey's test between individual group pairs. If the p value of Levene's test was less than 0.05, Welch's ANOVA was chosen to test significant difference between groups. If the p value of Welch's ANOVA was less than 0.05, significant differences were assessed by the Games-Howell test between groups. If ANOVA or Welch's ANOVA yielded a $p \geq 0.05$, no significant difference was present.

RESULTS

The gamma-ray spectra, dose rate, leakage of radio wave and changes of static magnetic field were measured at the site of PET/CT equipment before installation. The gamma-ray spectra from 0 to 2,000 keV for on-A, on-B and off settings are shown in Figure 2(a), 2(b) and 2(c). The real times, live times and calculated count per second for each measurement were as belows ; real time=263.3, live time=256.2 sec, 333.0 cps for Figure 2(a), real time=599.3 sec, live time=576.3 sec, 2755.43 cps for Figure 2(b) and real time=5907.2 sec, live time=5895.9 sec, 298.67 cps for Figure 2(c), respectively. Table 1

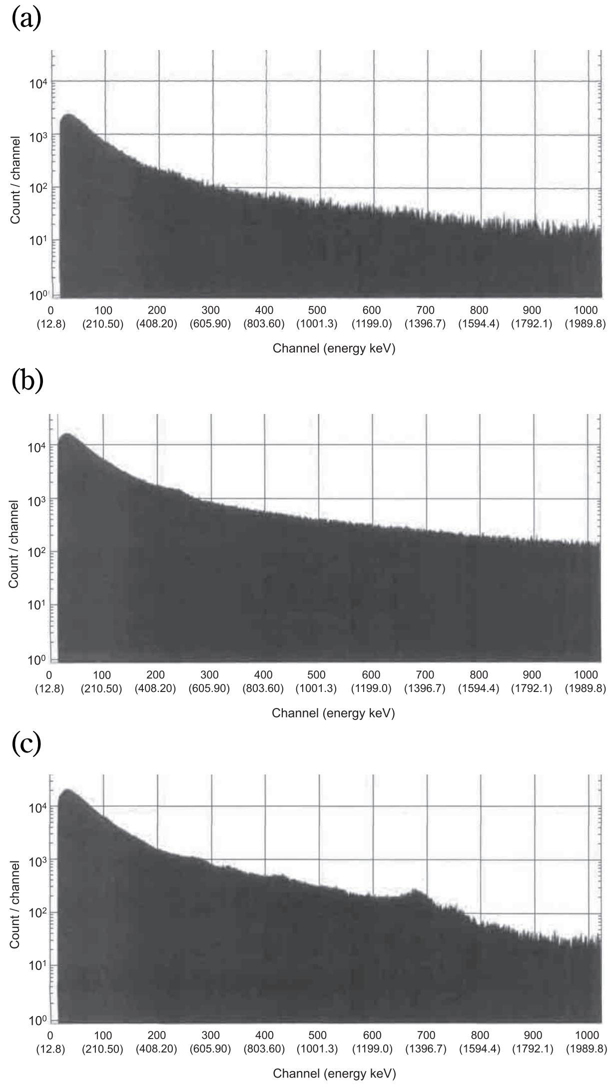

Figure 2 : The results of the gamma-ray spectra from 0 to 2,000 keV are shown. (a) Spectrum measured on running target-A. (b) Spectrum measured on running target-B. (c) Spectrum measured on idle cyclotron.

Table 1 : The results of the dose rate at the location at the center of the PET detector according to each target. The dose rate with the cyclotron operating using target B was higher than that using target A. The same trend was observed using different types of survey meters.

	Ionization chamber type survey meter (μSv/h)		Scintillation type survey meter (μSv/h)	
Target	A	B	A	B
Dose rate	0.42	2	0.34	1.8

shows the results of dose rate measurement using an ionization chamber type survey meter and a scintillation type survey meter. The gross areas of these spectra were 833.0 cps for on-A, 2755.4 cps for on-B and 298.7 cps for off, respectively. The longitudinal change of the leakage of radio wave is shown in Figure 3. When the cyclotron was started, an increase of the maximum power of the receiving electric field was observed. There was small fluctuation when the cyclotron was running. Table 2 shows the changes of the static magnetic field for periods when the cyclotron was on and then shut off. The maximum static magnetic field was less than 40 μT when the cyclotron was running. The changes of alternating magnetic field for running and stopping the cyclotron are shown in Figure 4(a) and 4(b). Results of direct-current fluctuating magnetic field measurement are shown in Table 3-a and 3-b. After installation of PET/CT equipment directly above the cyclotron, the natural background of the PET detector

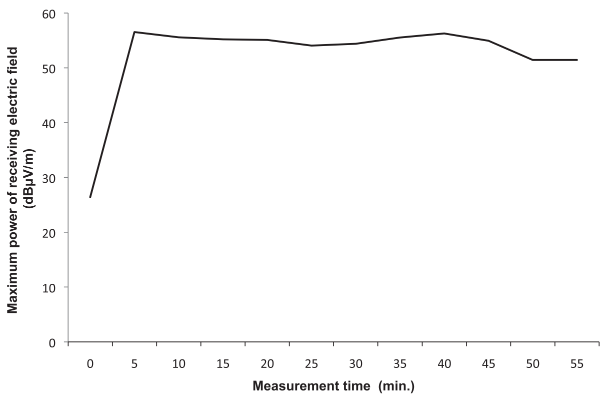

Figure 3 : The longitudinal change of leakage of radio waves as a function of measurement time.

Table 2 : The results of static magnetic field measurement for both the running and idle cyclotron. X, Y and Z were magnitude of magnetic field along each direction. The resultant value was computed from the sum of their sum of squares. Some increase of the static magnetic field was observed when the cyclotron was running.

During running the cyclotron (μT)				During stopping the cyclotron (μT)			
X	Y	Z	Resultant value	X	Y	Z	Resultant value
-20.5	-32.1	4.6	38.4	-26.3	-5.6	-14.3	30.4

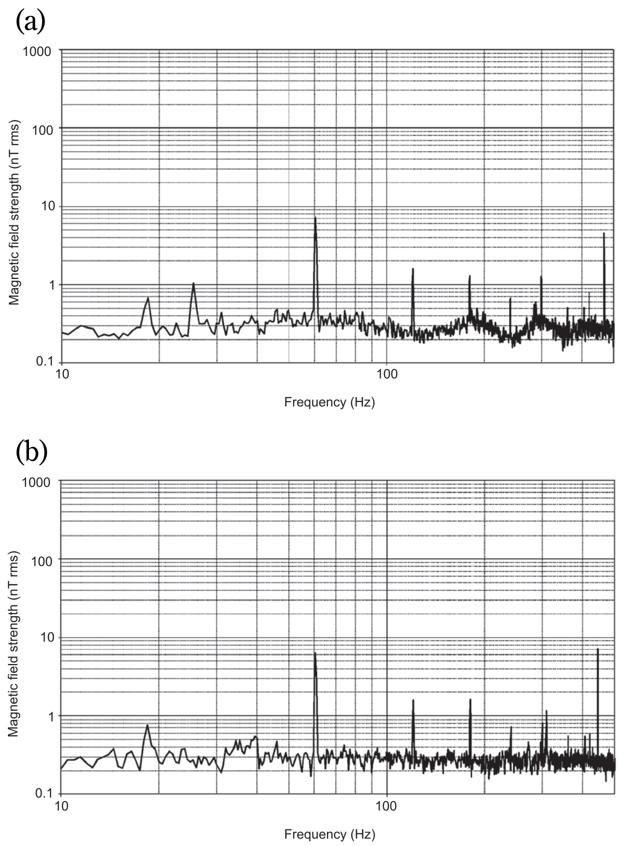

Figure 4 : The results of alternating magnetic field (a) when the cyclotron was running, (b) when the cyclotron was idle.

Table 3 : The results of direct-current fluctuating magnetic field measurement for both the running and idle cyclotron.
3-a : The results of the range of fluctuation of the magnetic field for the running and idle cyclotron. The resultant values for both the running and idle steady state were the same.

(μT)

X		Y		Z		Resultant values	
Running state	Idle state	Running state	Idle state	Running state	Idle state	Running state	Idle state
0.013	0.043	0.016	0.052	0.022	0.049	0.030	0.030

3-b : The range of fluctuating magnetic field during the transition from running to idle cyclotron. The range for the transition time was approximately one hundred times higher than that during steady state.

(μT)

X	Y	Z	Resultant Value
4.61	3.35	29.17	29.82

in the range from 50 keV to 750 keV for the running and idle cyclotron was measured for prompts, delays and true counts at coincidence detection. The results are shown in Figure 5. The result of emission mode measurement with the energy window from 350 to 650 is shown in Figure 6.

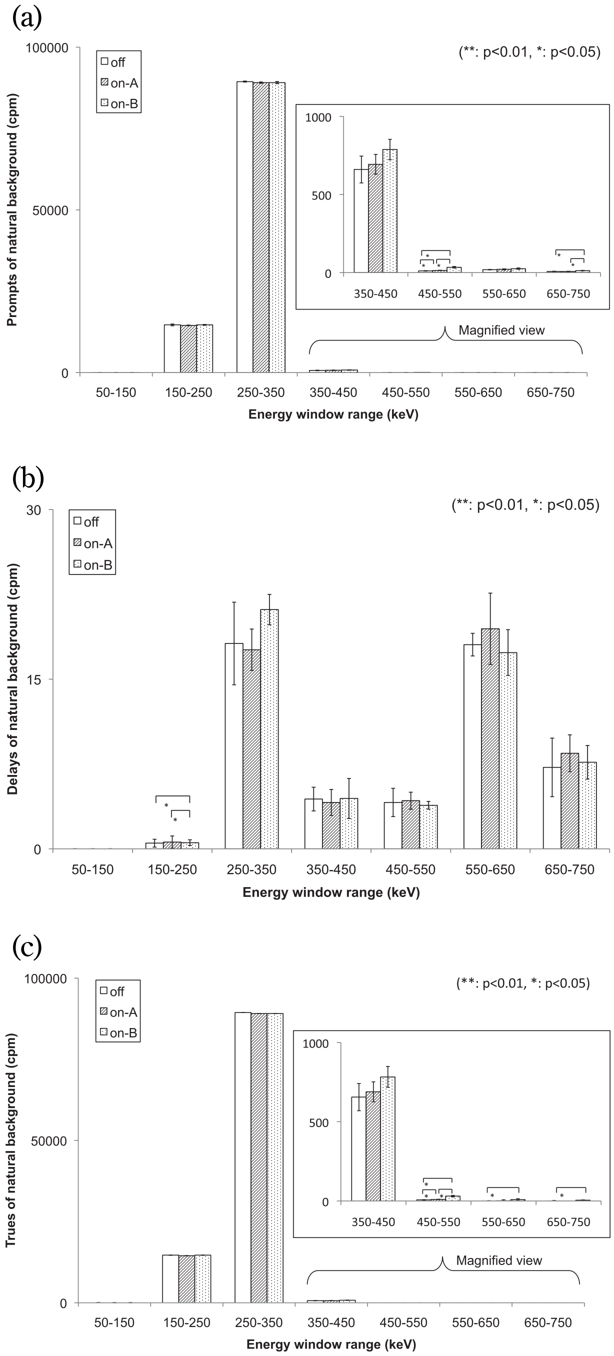

Figure 5 : The natural background of the PET detector for the running and idle cyclotron. (a) Results of prompt counts at coincidence detection. (b) Results of delays counts at coincidence detection. (c) Results of true counts at coincidence detection. There were some significant differences among off, on-A and on-B on prompts, delays and true counts at coincidence detection over 350 keV.

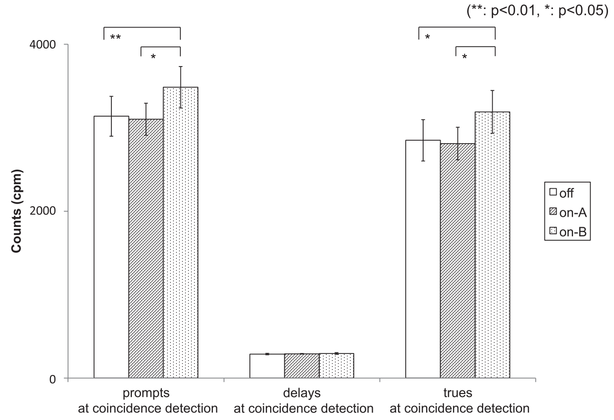

Figure 6 : The results of emission mode measurement. The differences between on-B and both off and on-A were statistically significant.

DISCUSSION

In Japan, the radiation controlled areas that are able to use unsealed radioisotopes have been strictly regulated by law in order to prevent radiation hazards. The effective dose limit at regions of regular entry is 1 mSv/week, the control area boundary is 1.3 mSv/week and the site boundary is 0.25 mSv per three months. All facilities that use unsealed radio isotopes must keep the radiation leakage within regulated limits, and must present a simulation of the dosages within the facility to authorities to obtain a building permit. Our PET/CT facility for small animals was built on a preexisting building with repair work. The previous purpose of this building was a hospital ward for brachytherapy that used ^{226}Ra, ^{137}Cs and ^{198}Au. The building was built according to the law and regulations for brachytherapy ; the thickness of concrete that were used for floors, ceils and walls were based on those regulations. When the plan was established to renovate the building as a PET/CT facility for small animals, the effective dose at each boundary area had to be calculated, with the legal limitation for one-day radiation dose at 370 MBq in one room and 270 MBq in any additional rooms. From the results of our calculations, the concrete thicknesses were sufficient to satisfy these regulations. This is the reason that the concrete thickness of the floor was 30 cm. The calculated effective dose of the cyclotron at the position of the PET/CT equipment was 136.23 μSv/week. Our cyclotron system had been installed only for clinical use before the PET/CT equipment for small animals was installed. After careful consideration, the second floor of the building that housed the cyclotron system was selected as the best place to install the PET/CT equipment because the distance between the cyclotron and PET/CT equipment was short, and would result in optimally short delivery times. Though the effective dose limit at the second floor that was directly above the cyclotron was within the limitations of the regulations, the influences of radio waves, and static and fluctuating magnetic fields that are generated by a running cyclotron remained concerns. This was the impetus behind the present research.

Before installation of PET/CT equipment, gamma-ray spectrum and dose rate, leakage of radio waves and static and fluctuated magnetic fields were evaluated at the position at the center of the PET detector. The shapes of gamma-ray spectra from 0 to 2000 keV for on-A, on-B and off settings were almost same, and there was no specific peak on the spectra, for instance at 511 keV. The results of the dose rate for on-B evaluated by the ionization chamber type survey meter and scintillation type survey meter were higher than that of on-A. The gross area of the spectra of on-B was also higher than that of on-A and off. This increase indicated the influence of the Compton scatter of high-energy second gamma rays produced by neutrons that leaked from the running cyclotron. No additional neutron radiation was detected on the second floor using neutron dosemeter (Hitachi-Aloka Medical, Ltd., MyDose mini PDM-313). It was thought that the low-energy gamma rays were not able to make peaks on the spectrum clearly. In this measurement, a 511-keV peak that would indicate electron pair formation was not observed at the center of PET detector when the cyclotron was running. This indicated that only the background was boosted by the low-energy gamma rays when the cyclotron was running.

The longitudinal change of the leakage of radio waves from the cyclotron off to cyclotron on was observed. When the cyclotron was started, the increase of maximum power of the receiving electric field was detected at approximately 60 dB. Though an increase of the maximum power of the receiving electric field was observed, it was confirmed that there was small fluctuation when the cyclotron was running. If this result is compared to the electric intensity that is used for immunity tests for medical equipment, the minimum intensity of the latter is 1 V/m (=120 dBμV/m) while our result was much smaller. This indicated that the leakage of radio waves was not a concern for the PET/CT equipment.

The changes of the static magnetic field for the running and idle cyclotron were evaluated using a variable magnetic field analyzer. The resultant value for the static magnetic field when the cyclotron was running was approximately 40 μT, and it was thought that such a static magnetic field would not impact the PET equipment. The alternating magnetic field changed from 40 nT to 3 nT when the cyclotron was turned off. It was understood that their compositions were 60 Hz, and the multiples of 60 Hz refer to both Figures 4(a) and (b). It was found that this alternating magnetic field was due to the commercial power source. Although there is no appropriate standard to compare with our results, this power was sufficiently smaller than the value of class A in IT-1004 specification of the Japan Electronics and Information Technology Industries Association (JEITA) (=1256 nT) (6). The resultant values of direct-current fluctuating magnetic fields in the running and idle status were under 0.1 μT. The maximum range of direct-current fluctuating magnetic field for the transition from cyclotron on to off was approximately 30 μT. These values were much smaller than the value of JEITA, indicating that there was no effect of the fluctuating magnetic field on the PET equipment.

After installation of the PET/CT equipment, the effect of the cyclotron on the background was evaluated. Before evaluation of the background, the natural background of the detector was measured. The natural background has to be evaluated carefully because the sensitivity of the PET equipment for animals is small due to the small photo-fraction of the detectors as well as relatively poor energy resolution (7). Figure 5 showed that there was almost no background over 350 keV on all statuses (on-A, on-B and off). There were some significant differences among off, on-A and on-B on prompts, delays and true counts at coincidence detection over 350 keV. All results indicated that the counts were increased when the target B was used. The same trend was observed in the results of emission mode measurement though there was no significant difference between off and on-A. These results indicated that running the cyclotron with target B, which is the target nearest to the PET detector, will result in an increased-count PET measurement. It was thought that the reasons for the influence by target B were the distance and the direction of the beam. But since the increase of the count by cyclotron running with target B was approximately 300 cpm, it was thought that this increase would not influence the results of

PET images of small animals. In our facility, currently administrated radioactivity of the radiotracer to the small animal is approximately 10 MBq and 90 minutes scan is performed for dynamic study. Mathematically, approximately 5.6 MBq is remained when the scan is finished. After considering the counting efficiency of the PET detector or any other condition, it was thought that 300 cpm (=5 cps) is very small to influence the results of PET images. An advanced evaluation will be needed to evaluate the precision of the PET measurement using an ultra-low activity range.

CONCLUSIONS

In this study, the impact of the cyclotron on small-animal PET/CT equipment installed directly above the cyclotron was evaluated. Though there were no influence of the radio waves or static and fluctuating magnetic fields that are generated by the running cyclotron, an increase of radiation dose was observed. Careful attention should be paid to this phenomenon when very low-radioactivity PET measurement is performed in such a setting.

CONFLICT OF INTEREST

The authors have no conflicts of interest to declare.

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