^{18}F-FDG EXTERNAL RADIATION DOSE RATES IN DIFFERENT BODY REGIONS OF PET-MRI PATIENTS

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To determine the factors affecting the external radiation dose rates of patients undergoing PET-MRI examinations and to assess the trends of these differences, we measured the changes in the dose rates of ^{18}F-FDG during a set period of time for each body region. Consistent with theoretical predictions, the dose rate decreased over time in patients undergoing PET-MRI examinations. Furthermore, immediately after the ^{18}F-FDG injection, the dose rate in the chest region was the highest, followed by the abdominal region, the head region, and the foot region. The dose rate decreased drastically as time passed, by 2.47-fold, from 339.23±74.70 mSv h^{-1} (6.73±5.79 min) at the time point immediately after the ^{18}F-FDG injection to 102.71±26.17 mSv h^{-1} (136.11±25.64 min) after the examination. In the foot region, there were no significant changes over time, from 32.05±20.23 mSv h^{-1} (6.73±5.79 min) at the time point immediately after the ^{18}F-FDG injection, to 23.89±9.14 mSv h^{-1} (136.11±25.64 min) after the examination. The dose rate is dependent on the individual characteristics of the patient, and differed depending on the body region and time point. However, the dose rates were higher in patients who had a lower body weight, shorter stature, fewer urinations, lower fluid intake, and history of diabetes mellitus. To decrease radiation exposure, it is difficult or impossible to change factors inherent to the patient, such as sex, age, height, body weight, obesity, and history of diabetes mellitus. However, factors which can be changed, such as the ^{18}F-FDG dose, fasting time, fluid intake, number of urinations, and contrast agent dose can be controlled to minimize the external radiation exposure of the patient.

Keywords: ^{18}F-FDG, PET-MRI, External Radiation Dose Rate, Influence Factor

1. INTRODUCTION

It is known that aerobic and anaerobic glycolysis is more accelerated in tumor cells than in normal cells. ^{18}F-fluorodeoxyglucose (^{18}F-FDG) has been used successfully in diagnosing various types of cancer, and its use has been increasing. ^{18}F-FDG, a glucose analog labeled with ^{18}F, is the most commonly used radioactive tracer in PET imaging, as it provides information regarding abnormal glucose metabolism. Hence, it is used not only in malignant tumors, but also in the diagnosis of various diseases, such as epilepsy and Alzheimer's disease. Regions where ^{18}F-FDG absorption is increased can be accurately determined from PET imaging to serve as a guide for histological examination or to determine the site of surgical resection [1-10].

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A full body scan PET-MRI examination is performed 45 min to 60 min after intravenous injection of ^{18}F-FDG in patients who have been fasting for 4-6 hour. While waiting for PET-MRI examination, if physical activity is performed, the muscles increase its consumption of ^{18}F-FDG. Therefore, the patient is instructed to rest. Furthermore, if the patient is anxious, the ^{18}F-FDG consumption of the neck muscles increases, which can sometimes be confused with lymph node consumption. Therefore, 5-10 mg of diazepam is sometimes administered orally. The half-life of ^{18}F-FDG is 109.8 min, and its maximum energy is 0.63 MeV. According to reports by the International Commission on Radiological Protection (ICRP) and the Radiation Internal Dose Information Center (RIDIC), the effective doses of ^{18}F-FDG for 15-year-olds and adults over 21 y are 0.024 mSv MBq^{-1} and 0.020 mSv MBq^{-1}, respectively. Because the time required to estimate radiation exposure to the guardians of patients ad-

ministered ^{18}F-FDG is 1.6 h, the effective dose for non-patients is not to exceed the normal dose limit of 1 mSv, the maximum dose possible for administration is 1,330 MBq [11].

According to the 2000 report from the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), even in patients who have received the same radiological examination, radiation exposure can vary 10 to 20 fold depending on the healthcare provider. UNSCEAR also reported that the highest source of exposure from artificial radiation is medical exposure. ^{18}F-FDG injected into patients for PET-MRI examinations not only exposes the patient to radiation, but the patient's guardians, and others visiting the radiology clinic are not guaranteed to be protected from radiation exposure unless the healthcare provider implements strict management and regulations [12-18]. Considering that the total radiological exposure from medical radiation is high, the Principle of Optimisation of Protection in medical exposure is significant. According to the International Commission on Radiological Protection (ICRP) and based on the Principle of Justification, there are no maximum dose limits (The Principle of Application of Dose limits). However, various approaches to minimize radiation exposure are necessary. In Korea, the first PET-MRI scanner in Asia was introduced in the Department of Radiological Medicine at Pusan National University Hospital in July 2011, and since 2012, scanners at Yeongnam National University Hospital and Seoul National University Hospital also have been in operation [19].

Therefore, in this study, our objective was to measure the external radiation dose rate for each body region in patients who have been administered ^{18}F-FDG for PET-MRI examinations, and to use this data as a basis to reduce exposure as low as reasonably achievable for patients, radiology-related healthcare workers, and patient guardians.

2. Materials and Methods

The instruments for analysis were a radiation survey meter, digital scale, digital height rod, plasma glucose monitor (range, 10 mg dL^{-1}–600 mg dL^{-1}), dose calibrator (range, ^{99m}Tc maximum 240 GBq; resolution, 0.001 MBq; accuracy, ±2%; linearity ± 2%; measurement time, 2 s), and a survey questionnaire. The external radiation dose rate for patients was measured using a personal radiation detector (RadEye G-10, energy compensated GM-tube). the administration of ^{18}F-FDG, the sex, age, height, body weight, body mass index (BMI), diabetes mellitus status, plasma glucose level, fasting time, and usage of contrast agents were surveyed. After the ^{18}F-FDG injection, the dose rates were measured using the GM tube for each time point, distance (10, 50, and 100 cm from the patient's skin surface), and body region (head, chest, abdominal, and foot regions). time points for measurement were set based on patient behaviors which lead to drastic changes in dose rate, based on the preliminary survey. Time point 1 was set immediately after the ^{18}F-FDG injection (within 10 min), time point 2 was set within the waiting period after the ^{18}F-FDG injection but before the PET-MRI examination and the first urination, time point 3 was set immediately after urination, and time point 4 was set immediately after the PET-MRI examination (Table 1).

Fluid intake before and after the ^{18}F-FDG injection, the contrast agent dose, the number of urinations between the ^{18}F-FDG injection and PET-MRI scan, and the number of urinations after the PET-MRI scan were determined by observation. The ^{18}F-FDG dose was measured using a dose calibrator. The ^{18}F-FDG dose was determined based on the patient's characteristics, with a minimum of 173.16 MBq, averaging 226.44 MBq, and a maximum of 320.05 MBq. At the hospital where the study was performed, an average of 222 MBq for adults is the guideline dose for the injection. The subjects of the study were 48 PET-MRI patients who were enrolled in the study after providing their informed consent for participation. The patients were admitted between March and April 2013 to Y University Hospital, in the Yeongnam region of Korea, where the first simultaneous PET-MRI scanner was installed and operated. The measured data was analyzed by frequency

Table 1. Time Points for Dose Rate Measurement.

Classification		mean ± SD (min)
Time point 1	Within 10 min after ^{18}F-FDG injection	6.73 ± 5.79
Time point 2	Before the first urination and after ^{18}F-FDG injection	42.39 ± 6.26
Time point 3	After the first urination after the ^{18}F-FDG injection	47.28 ± 7.24
Time point 4	Immediately after PET-MRI	136.11 ± 25.64

and percentage; data is reported as the mean and standard deviation and multiple regression analyses were performed using the SPSS Win 17.0 statistical software package.

3. Results

3.1 General characteristics of the subjects

The general characteristics of the subjects were as follows: 15 (31.3%) were men and 33 (68.8%) were women; 21 (43.8%) were younger than 50 years old and 27 (56.3%) were older than 50 years old. 24 (50.0%) were shorter than 160 cm and 24 (50.0%) were 160 cm or taller; 23 (47.9%) were less than 60 kg and 25 (52.1%) were 60 kg or heavier. For obesity (body mass index), 1 (2.1%) was underweight, 25 (52.1%) were of normal body weight, 11 (22.9%) were overweight, and 11 (22.9%) were obese. 3 (7.7%) had diabetes mellitus and 36 (92.3%) did not. The plasma glucose level was normal in 47 (97.9%) and abnormal in 1 (2.1%). For the ^{18}F-FDG dose, 28 (58.3%) were administered less than 222 MBq and 20 (41.7%) were administered 222 MBq or more. For fasting time, 11 (22.9%) had fasted for less than 10 hours and 37 (77.1%) had fasted for more than 10 hours. Fluid intake before admission, 34 (72.3%) consumed less than 250 mL and 13 (27.7%) consumed 250 mL or more. Fluid intake after admission, 12 (25.0%) consumed less than 250 mL and 36 (75.0%) consumed 250 mL or more. The number of urinations between the ^{18}F-FDG injection and immediately before the PET-MRI examination, 45 (93.8%) urinated once and 3 (6.3%) urinated twice. 47 (97.9%) were administered contrast agents and 1 (2.1%) was not administered a contrast agent (Table 2).

3.2 Changes in the dose rate in each body region at each time point

Results of the dose rate measured 10 cm from the body surface of PET-MRI patients showed that the highest dose rate in each region were as follows: head region, time point 2 (42.39±6.26 min) 181.33±44.92 μSv h^{-1}; chest region, time point 1 (6.73±5.79 min) 339.23±74.70 μSv h^{-1}; abdominal region, time point 1 (6.73±5.79 min) 265.35±61.12 μSv h^{-1}; and foot region, time point 3 (47.28±7.24 min) 36.84±23.06 μSv h^{-1} (Table 3) (Figure 1).

Table 2. General Characteristics of the Subjects.

Item	Classification	n (%)
Sex	Male	15 (31.3)
	Female	33 (68.8)
Age	Less than 50 y	21 (43.8)
	50 y or over	27 (56.3)
Height	Shorter than 160 cm	24 (50.0)
	160 cm or taller	24 (50.0)
Body weight	Less than 60 kg	23 (47.9)
	60 kg or over	25 (52.1)
Body Mass Index (BMI, kgm^{-2})	Underweight (BMI < 18.5)	1 (2.1)
	Normal (18.5 ≤ BMI ≤ 24.9)	25 (52.1)
	Overweight (25.0 ≤ BMI ≤ 29.9)	11 (22.9)
	Obese (BMI ≥ 30.0)	11 (22.9)
Diabetes mellitus	Present	3 (7.7)
	Absent	36 (92.3)
Plasma glucose level	Normal	47 (97.9)
	Abnormal	1 (2.1)
^{18}F-FDG dose	Less than 222 MBq	28 (58.3)
	222 MBq or more	20 (41.7)
Fasting time	Less than 10 h	11 (22.9)
	10 h or more	37 (77.1)
Fluid intake before admission	less than 250 mL	34 (72.3)
	250 mL or more	13 (27.7)
Fluid intake after admission	less than 250 mL	12 (25.0)
	250 mL or more	36 (75.0)
Number of urinations (after ^{18}F-FDG injection and before the PET-MRI examination)	Once	45 (93.8)
	Twice	3 (6.3)
Use of contrast agents	Yes	47 (97.9)
	No	1 (2.1)
	Total	48(100.0)

*Diabetes mellitus, fluid intake before admission, and fluid intake after admission have missing values.

Table 3. Changes in External Radiation Dose rate for Each Body Region at Each Time Point.

Classification		mean ± SD (μSv h^{-1})
Head region	Time point 1 (6.73 ± 5.79 min)	171.71 ± 45.71
	Time point 2 (42.39 ± 6.26 min)	181.33 ± 44.92
	Time point 3 (47.28 ± 7.24 min)	170.67 ± 46.35
	Time point 4 (136.11 ± 25.64 min)	109.06 ± 30.06
Chest region	Time point 1 (6.73 ± 5.79 min)	339.23 ± 74.70
	Time point 2 (42.39 ± 6.26 min)	215.46 ± 50.59
	Time point 3 (47.28 ± 7.24 min)	196.73 ± 47.56
	Time point 4 (136.11 ± 25.64 min)	102.71 ± 26.17
Abdominal region	Time point 1 (6.73 ± 5.79 min)	265.35 ± 61.12
	Time point 2 (42.39 ± 6.26 min)	220.24 ± 48.41
	Time point 3 (47.28 ± 7.24 min)	170.54 ± 47.45
	Time point 4 (136.11 ± 25.64 min)	105.12 ± 26.22
Foot region	Time point 1 (6.73 ± 5.79 min)	32.05 ± 20.23
	Time point 2 (42.39 ± 6.26 min)	33.35 ± 17.49
	Time point 3 (47.28 ± 7.24 min)	36.84 ± 23.06
	Time point 4 (136.11 ± 25.64 min)	23.89 ± 9.14

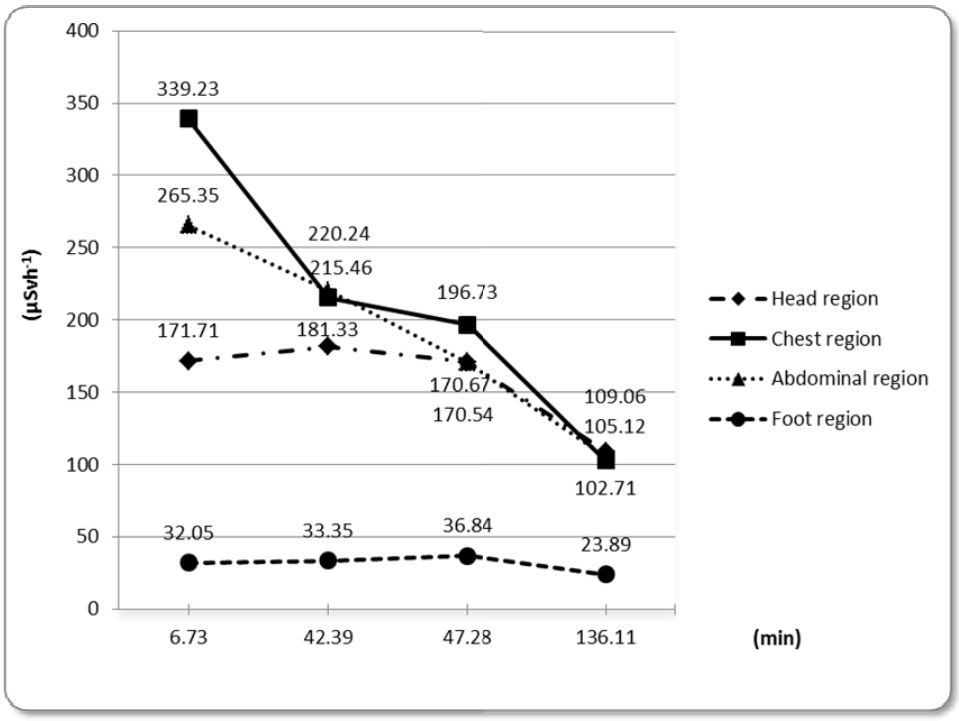

Figure 1. Changes in dose rate for each body region and time point.

3.3 Factors that affect the dose rates in the head region at each time point

To determine the factors that affect the external radiation dose rate in the head region of patients undergoing PET-MRI examinations, the external radiation dose rate was set using the dependent variables of age, height, body weight, ^{18}F-FDG dose, fasting time, fluid intake before admission, fluid intake after admission, and the number of urinations, whereas the contrast agent dose was set using the independent variables of the multiple linear regression analysis which was performed for each time point. The results showed that the ^{18}F-FDG dose was the factor with the most significant effect on dose rate. At time point 1 (6.73±5.79 min) the ^{18}F-FDG dose, body weight, and height, respectively, affected the dose rate. With a higher ^{18}F-FDG dose,

Table 4. Factors that Affect the Dose Rates in the Head Region at Each Time Point.

Independent variables	Time point 1 (6.73 ± 5.79 min)		Time point 2 (42.39 ± 6.26 min)		Time point 3 (47.28 ± 7.24 min)		Time point 4 (136.11 ± 25.64 min)	
	β	t(p)	β	t(p)	β	t(p)	β	t(p)
(Constant)		2.318 (0.027)		4.419 (0.000)		3.646 (0.001)		0.602 (0.552)
Age	-0.003	-0.019 (0.985)	-0.139	-1.108 (0.277)	-0.055	-0.449 (0.657)	0.001	0.004 (0.997)
Height	-0.224	-1.312 (0.199)	-0.485	-3.156 (0.004)	-0.390	-2.624 (0.013)	0.058	0.300 (0.766)
Body weight	-0.317	-1.545 (0.132)	0.094	0.511 (0.613)	0.092	0.513 (0.611)	0.105	0.450 (0.656)
^{18}F-FDG dose	0.467	3.145 (0.004)	0.546	4.124 (0.000)	0.611	4.720 (0.000)	0.481	2.846 (0.008)
Fasting time	0.169	1.297 (0.204)	0.049	0.423 (0.675)	0.020	0.177 (0.861)	0.258	1.742 (0.091)
Fluid intake before admission	-0.112	-0.814 (0.422)	0.036	0.302 (0.765)	0.040	0.337 (0.738)	0.036	0.229 (0.820)
Fluid intake after admission	-0.135	-1.012 (0.319)	-0.046	-0.382 (0.705)	-0.116	-0.993 (0.328)	-0.083	-0.549 (0.587)
Fluid intake	-0.033	-0.256 (0.799)	-0.195	-1.668 (0.106)	-0.229	-2.020 (0.052)	-0.156	-1.054 (0.300)
Number of urinations	-0.142	-1.051 (0.301)	-0.308	-2.543 (0.017)	-0.241	-2.052 (0.049)	-0.151	-0.984 (0.333)
Contrast agent dose	0.061	0.369 (0.715)	-0.097	-0.647 (0.523)	-0.098	-0.682 (0.500)	-0.304	-1.628 (0.114)
F (p-value)	3.829 (0.002)		5.710 (0.000)		6.024 (0.000)		2.266 (0.040)	
R^2	0.553		0.663		0.660		0.422	

lower body weight, and shorter height, the external radiation dose rate was higher (P<0.001). At time points 2 (42.39±6.26 min) and 3 (47.28±7.24 min), the ^{18}F-FDG dose, height, and number of urinations, respectively, affected the dose rate. The dose rate was higher with a higher ^{18}F-FDG dose, shorter stature, fewer urinations, and lower fluid intake (P<0.001). At time point 4 (136.11±25.64 min), the ^{18}F-FDG dose, contrast agent dose, and fasting time, respectively, affected the dose rate. The dose rate was higher with a higher ^{18}F-FDG dose, lower contrast agent dose, and longer fasting time (P<0.001) (Table 4).

3.4 Factors that affect the dose rates in the chest region at each time point

To determine the factors that affect the dose rate in the chest region of patients undergoing PET-MRI examinations, the dose rate dependent variable was set using age, height, body weight, ^{18}F-FDG dose, fasting time, fluid intake before admission, fluid intake after admission, and number of urinations, whereas the independent variables were set using the contrast agent dose. Multiple linear regression analyses were performed for each time point. The results showed that ^{18}F-FDG dose was the factor with the most significant effect on dose rate. time point 1 (6.73±5.79 min), the ^{18}F-FDG dose, age, and height, in that order, affected the dose rate. The dose rate was higher with a higher ^{18}F-FDG dose, lower age, and shorter stature (P < 0.001). At time point 2 (42.39±6.26 min), the ^{18}F-FDG dose, height, and fluid intake, respectively, affected the dose rate. The dose rate was higher with a higher ^{18}F-FDG dose, shorter stature, and lower fluid intake (P<0.01). At time point 3 (47.28±7.24 min), the ^{18}F-FDG dose, fluid intake, and body weight, respectively, affected the dose rate. The dose rate was higher with a higher ^{18}F-FDG dose, lower fluid intake, and lower body weight (P<0.001). At time point 4 (136.11±25.64 min), the ^{18}F-FDG dose, fasting time, body weight, and height, respectively, affected the dose rate. The dose rates were higher with a higher ^{18}F-FDG dose, longer fasting time, lower body weight, and shorter stature (P<0.01) (Table 5).

Table 5. Factors that Affect the Dose Rates in the Chest Region at Each Time Point.

Independent variables	Time point 1 (6.73 ± 5.79 min)		Time point 2 (42.39 ± 6.26 min)		Time point 3 (47.28 ± 7.24 min)		Time point 4 (136.11 ± 25.64 min)	
	β	t(p)	β	t(p)	β	t(p)	β	t(p)
(Constant)		2.646 (0.013)		2.849 (0.008)		1.999 (0.054)		-1.063 (0.296)
Age	-0.326	-2.488 (0.018)	-0.130	-0.929 (0.361)	-0.152	-1.239 (0.225)	-0.004	-0.030 (0.976)
Height	-0.194	-1.227 (0.229)	-0.348	-2.031 (0.052)	-0.143	-0.964 (0.343)	0.343	1.963 (0.059)
Body weight	-0.153	-0.804 (0.428)	-0.003	-0.017 (0.987)	-0.212	-1.189 (0.244)	-0.396	-1.885 (0.069)
^{18}F-FDG dose	0.671	4.873 (0.000)	0.585	3.962 (0.000)	0.651	5.042 (0.000)	0.420	2.759 (0.010)
Fasting time	-0.047	-0.392 (0.698)	0.106	0.819 (0.420)	0.110	0.973 (0.338)	0.404	3.022 (0.005)
Fluid intake before admission	0.090	0.711 (0.482)	0.062	0.470 (0.642)	-0.035	-0.292 (0.772)	-0.050	-0.354 (0.726)
Fluid intake after admission	-0.094	-0.756 (0.456)	0.084	0.627 (0.536)	-0.048	-0.410 (0.685)	-0.034	-0.247 (0.806)
Fluid intake	-0.160	-1.327 (0.194)	-0.169	-1.291 (0.207)	-0.215	-1.900 (0.067)	-0.200	-1.498 (0.144)
Number of urinations	-0.128	-1.022 (0.315)	-0.158	-1.170 (0.252)	-0.170	-1.447 (0.158)	0.083	0.599 (0.553)
Contrast agent dose	-0.029	-0.192 (0.849)	-0.102	-0.610 (0.546)	0.076	0.533 (0.598)	-0.076	-0.450 (0.656)
F (p-value)	4.960 (0.000)		4.023 (0.002)		6.081 (0.000)		3.508 (0.003)	
R^2	0.615		0.581		0.662		0.531	

Table 6. Factors that Affect the Dose Rates in the Abdominal Region at Each Time Point

Independent variables	Time point 1 (6.73 ± 5.79 min)		Time point 2 (42.39 ± 6.26 min)		Time point 3 (47.28 ± 7.24 min)		Time point 4 (136.11 ± 25.64 min)	
	β	t(p)	β	t(p)	β	t(p)	β	t(p)
(Constant)		0.933 (0.358)		1.294 (0.206)		-0.603 (0.551)		-1.730 (0.093)
Age	-0.114	-0.951 (0.349)	-0.218	-1.702 (0.099)	-0.108	-0.808 (0.425)	-0.052	-0.348 (0.730)
Height	0.086	0.594 (0.557)	0.043	0.272 (0.788)	0.170	1.049 (0.302)	0.465	2.582 (0.015)
Body weight	-0.361	-2.079 (0.046)	-0.375	-2.002 (0.055)	-0.358	-1.844 (0.075)	-0.434	-2.006 (0.054)
^{18}F-FDG dose	0.709	5.633 (0.000)	0.669	4.955 (0.000)	0.708	5.032 (0.000)	0.495	3.154 (0.004)
Fasting time	-0.067	-0.608 (0.547)	-0.064	-0.542 (0.592)	-0.064	-0.521 (0.606)	0.271	1.967 (0.058)
Fluid intake before admission	0.003	0.025 (0.980)	-0.088	-0.728 (0.472)	0.097	0.749 (0.459)	0.021	0.145 (0.886)
Fluid intake after admission	-0.233	-2.059 (0.048)	-0.063	-0.516 (0.610)	-0.005	-0.036 (0.972)	0.009	0.062 (0.951)
Fluid intake	-0.105	-0.955 (0.347)	-0.098	-0.823 (0.417)	-0.103	-0.834 (0.411)	-0.119	-0.865 (0.394)
Number of urinations	-0.119	-1.045 (0.304)	-0.123	-1.000 (0.325)	-0.044	-0.342 (0.735)	0.114	0.800 (0.430)
Contrast agent dose	0.006	0.045 (0.964)	0.017	0.115 (0.910)	0.130	0.837 (0.409)	-0.081	-0.464 (0.646)
F (p-value)	6.566 (0.000)		5.388 (0.000)		4.623 (0.000)		3.119 (0.007)	
R^2	0.679		0.650		0.599		0.502	

Table 7. Factors that Affect the Dose Rates in the Foot Region at Each Time Point.

Independent variables	Time point 1 (6.73 ± 5.79 min)		Time point 2 (42.39 ± 6.26 min)		Time point 3 (47.28 ± 7.24 min)		Time point 4 (136.11 ± 25.64 min)	
	β	t(p)	β	t(p)	β	t(p)	β	t(p)
(Constant)		-1.155 (0.257)		-0.599 (0.554)		0.062 (0.951)		-1.416 (0.167)
Age	-0.035	-0.209 (0.836)	0.007	0.039 (0.969)	-0.053	-0.309 (0.759)	0.129	0.729 (0.472)
Height	0.081	0.405 (0.689)	-0.047	-0.218 (0.829)	-0.233	-1.127 (0.269)	0.197	0.923 (0.363)
Body weight	0.034	0.140 (0.890)	0.300	1.162 (0.255)	0.143	0.575 (0.569)	-0.076	-0.295 (0.770)
^{18}F-FDG dose	0.365	2.088 (0.045)	0.340	1.827 (0.078)	0.272	1.515 (0.140)	0.387	2.084 (0.045)
Fasting time	-0.018	-0.117 (0.908)	0.007	0.042 (0.967)	0.111	0.702 (0.488)	-0.087	-0.533 (0.598)
Fluid intake before admission	0.134	0.828 (0.414)	0.008	0.049 (0.961)	0.118	0.710 (0.483)	0.143	0.832 (0.412)
Fluid intake after admission	0.416	2.643 (0.013)	0.166	0.988 (0.332)	0.255	1.574 (0.126)	0.138	0.826 (0.415)
Fluid intake	0.145	0.950 (0.350)	0.126	0.763 (0.452)	-0.073	-0.466 (0.644)	0.095	0.582 (0.565)
Number of urinations	-0.055	-0.347 (0.731)	-0.128	-0.750 (0.459)	-0.052	-0.321 (0.750)	0.145	0.861 (0.396)
Contrast agent dose	0.232	1.198 (0.240)	0.240	1.143 (0.262)	0.391	1.964 (0.059)	0.115	0.557 (0.581)
F (p-value)	1.914 (0.081)		1.453 (0.207)		1.638 (0.142)		1.336 (0.256)	
R^2	0.382		0.334		0.346		0.301	

3.5 Factors that affect the dose rate in the abdominal region at each time point

To determine the factors that affect the dose rate in the abdominal region of patients undergoing PET-MRI examinations, the dose rate was set as the dependent variable, whereas age, height, body weight, ^{18}F-FDG dose, fasting time, fluid intake before admission, fluid intake after admission, number of urinations, and contrast agent dose were set as the independent variables. Multiple linear regression analyses were performed for each time point. The results showed that the ^{18}F-FDG dose was the factor with the most significant effect on the dose rate. At time point 1 (6.73±5.79 min), the ^{18}F-FDG dose, body weight, and fluid intake, respectively, affected the dose rate. The dose rate was higher with a higher ^{18}F-FDG dose, lower body weight, and with lower fluid intake ($P<0.001$). At time point 2 (42.39±6.26 min), the ^{18}F-FDG dose, body weight, and age, respectively, affected the dose rate. The dose rate was higher with a higher ^{18}F-FDG dose, lower body weight, and in younger patients ($P<0.001$). At time point 3 (47.28±7.24 min), the ^{18}F-FDG dose, body weight, and height, respectively, affected the dose rate. The dose rate was higher with a higher ^{18}F-FDG dose, lower body weight, and shorter stature, ($P<0.001$). At time point 4 (136.11±25.64 min), the ^{18}F-FDG dose, height, body weight, and fasting time respectively, affected the dose rate. The dose rate was higher with a higher ^{18}F-FDG dose, shorter stature, lower body weight, and longer fasting time ($P<0.01$) (Table 6).

3.6 Factors that affect the dose rates in the foot region at each time point

To determine the factors that affect the dose rate in the foot region of patients undergoing PET-MRI examinations, the dose rate was set as the dependent variable, whereas age, height, body weight, ^{18}F-FDG dose, fasting time, fluid intake before admission, fluid intake after admission, number of urinations, and contrast agent dose were set as independent variables, and with multiple linear regression analyses were performed for each time point. The results showed that the regression model did not fit any of the time points (Table 7).

4. Conclusion

To determine the factors affecting the external radiation dose rates of patients undergoing PET-MRI examinations and to assess the trends of these differences, we measured the changes in the dose rates of ^{18}F-FDG during a set period of time for each body region. Consistent with theoretical predictions, the dose rate decreased over time in patients undergoing PET-MRI examinations. Furthermore, immediately after the ^{18}F-FDG injection, the dose rate in the chest region was the highest, followed by the abdominal region, the head region, and the foot region. The dose rate decreased drastically as time passed, by 2.47-fold, from 339.23±74.70 μSv h^{-1} (6.73±5.79 min) at the time point immediately after the ^{18}F-FDG injection to 102.71±26.17 μSv h^{-1} (136.11±25.64 min) after the examination. In the foot region, there were no significant changes over time, from 32.05±20.23 μSv h^{-1} (6.73±5.79 min) at the time point immediately after the ^{18}F-FDG injection, to 23.89±9.14 μSv h^{-1} (136.11±25.64 min) after the examination.

The dose rate is dependent on the individual characteristics of the patient, and differed depending on the body region and time point. However, the dose rates were higher in patients who had a lower body weight, shorter stature, fewer urinations, lower fluid intake, and history of diabetes mellitus. In the regression analysis, the ^{18}F-FDG dose was shown to be the most dominant factor affecting the patient's external radiation dose rate in the head, chest, and abdominal regions. In the case of the foot region, the regression analysis model did not fit the data from any of the time points. In the head region, the ^{18}F-FDG dose, body weight, time, and contrast agent dose, respectively, affected the external radiation dose rate. In the chest region, the ^{18}F-FDG dose, age, height, fluid intake, body weight, and fasting time, respectively, affected the dose rate. In the abdominal region, the ^{18}F-FDG dose, body weight, and height, respectively, affected the dose rate. Body weight was the second most dominant factor for all time points.

To decrease radiation exposure, it is difficult or impossible to change factors inherent to the patient, such as sex, age, height, body weight, obesity, and history of diabetes mellitus. However, factors which can be changed, such as the ^{18}F-FDG dose, fasting time, fluid intake, number of urinations, and contrast agent dose can be controlled to minimize the external radiation exposure of the patient. In other words, after the PET-MRI examination, increasing the number of urinations and fluid intake, or decreasing fasting time, can be used as strategies to not only protect the patient, but also decrease the radiation exposure of radiology-related healthcare workers and patient guardians. As the ^{18}F-FDG dose most significantly affects the dose rate, the minimum dose for the patient's body weight must be used without affecting the image quality of the examination. As PET-MRI examinations are becoming increasingly common, a drastic increase in ^{18}F-FDG use is inevitable, from the ICRP's Principle of Justification. However, the exposed radiation dose must be as low as reasonably achievable, based on The Principle of Optimisation of Protection. Based on the results of our study, the following possible intervention strategies are recommended for the optimization of protection [20].

First, the minimum ^{18}F-FDG dose must be used based on the patient's body weight. Second, if another person must come into contact with a patient who has been administered ^{18}F-FDG, the person should be approach from the patient's foot region. Third, if possible, the patient should be approached after an amount of time has passed after ^{18}F-FDG administration. Fourth, the minimum fasting time required for the examination should be used. Fifth, Fluid intake and the number of urinations after the examination should be increased. Sixth, for diagnosis and protection from exposure, it should be considered that the dose rate is different depending on the body region. These intervention strategies can be implemented, assuming that the quality of the image is not affected [21]. In the future, there is a need for patient-control experiments to assess the effects of decreasing radiation exposure from examinations using ^{18}F-FDG, taking into consideration changes in dose rate in different regions of the body.

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