Very different external radiation doses in patients undergoing PET/CT or PET/MRI scans and factors affecting them

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Abstract

Our aim was to determine the external radiation dose rates of patients undergoing positron emission tomography/computed tomography (PET/CT) and PET/magnetic resonance imaging (MRI) examinations, and to assess the factors affecting these doses. *The external radiation dose rates (ERDR) from ^{18}F-FDG were measured* using the Geiger-Müller tube at a distance of 10, 50, and 100cm from the patients' skin surface from various body regions. *Results showed that* at 10cm from the body surface for PET/CT examinations, the ERDR immediately after ^{18}F-FDG i.v. injection at time points 1 and 4 was 522.19±189.59μSvh^{-1} and 256.36±74.94μSvh^{-1}, respectively. At 10cm from the body surface for PET/MRI examinations, the ERDR at time points 1 and 4 were 258.76±92.09μSvh-1 and 105.63±27.48μSvh^{-1}, respectively, always with a precipitous decrease over time. The ^{18}F-FDG dose was on average 1.93-fold higher and the ERDR was higher approximately 2.01 to 2.42-fold in PET/CT examinations than in PET/MRI examinations. In both PET/CT and PET/MRI patients, the ERDR was significantly higher with lower body weight, shorter stature, and fewer urinations etc. *In conclusion*, based on our results, the ERDR to patients from PET/CT scans at a distance of 10cm was twice as high than from the PET/MRI. Furthermore, to decrease ERDR to the patients, the dose injected should be adjusted to body weight and height. Factors like post injection fluid intake and urine bladder emptying, decrease ERDR. Other persons should keep a safe distance from the injected patient.

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Introduction

The age-standardized incidence rate (ASR) of cancer in Korea, as adjusted to the World Standard Population (2010), is 282.3 individuals per 100,000, and is higher than the average of 256.5 per 100,000 found in the countries of the Organization for Economic Cooperation and Development (OECD). The trend of ASR for cancer has increased from 219.9 individuals per 100,000 in 1999 to 304.8 in 2010, with an annual average increase of 3.5% [1-3].

The annual number of positron emission tomography/computed tomography (PET/CT) examinations, which use the radioactive agent ^{18}F-FDG for cancer diagnosis, has been drastically increasing each year, from 66 cases in 1994 to 308,663 in 2009, and 341,992 in 2010 [4]. However, recently developed PET-magnetic resonance imaging (PET/MRI) has the advantages of lower radiation exposure, better soft tissue contrast, and the ability to acquire images of various biochemical characteristics. Therefore, we predict that its everyday application will drastically increase as well.

It is known that aerobic and anaerobic glycolysis are more accelerated in tumor cells than in normal cells, thus, fluorine-18-fluorodeoxyglucose (^{18}F-FDG) has been used successfully to diagnose various types of cancer. Positron emission tomography/CT was developed in the late 1990s to overcome the limitations of conventional PET, including the lack of anatomical information and low resolution resulting from its underlying biochemical and physical principles, and was successfully commercialized in early 2000s [5-13]. In PET/CT studies, the total dose of radiation to which patients are exposed is higher than from PET only because of the additional CT radiation exposure. The patients' guardians and visitors are not usually protected from radiation exposure unless the healthcare provider implements strict regulations and management. According to a 2000 report from the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), even in patients who undertake the same radiological examination, radiation exposure can vary 10 to 20 fold depending on precautions issued by the healthcare provider [14, 15]. It is reported that the highest source of exposure from artificial radiation is from medical exposure [14-23], so, the Principle of Optimization of Protection in cases of medical exposure is important [16-23] and related protective measures are necessary. The International Commission on Radiological Protection

(ICRP), based on the Principle of Justification, established the maximum dose limits in 2007 but has not establish the maximum dose rate for medical patients [24].

The first PET/MRI scanner in Asia was introduced in Korea, in the Department of Radiological Medicine at Pusan National University Hospital in July 2011, and since 2012, more such scanners are in operation at Yeongnam National University Hospital and Seoul National University Hospital [25]. In this study, our objective was to measure the external radiation dose rate (ERDR) of patients who have been administered ^{18}F-FDG for PET/CT and PET/MRI and use it as a basis for making ionizing radiation exposure (RE) as low as reasonably achievable for the benefit of patients studied, for healthcare workers, and for patient guardians.

Subjects and methods

We used a radiation survey meter, digital scale, digital height rod, plasma glucose monitor (10-600mg/dL), a dose calibrator (range for technetium-99m (^{99m}Tc) maximum 240GBq, resolution of 0.001MBq, accuracy ±2%; linearity ±2% and counting time 2s), and a survey questionnaire. The patients' ERDR were measured using a personal radiation detector (RadEye G-10, energy compensated GM-tube).

Before the administration of ^{18}F-FDG, the sex, age, height, body weight, obesity, history of diabetes mellitus, plasma glucose level, fasting time, and whether contrast agents were recently injected were recorded. After the ^{18}F-FDG intravenous (i.v.) injection and at different time points, the ERDR were measured using the GM tube at a distance of 10, 50, and 100cm from the patient's skin surface from various specific body regions in the head, chest, and the abdomen.

The time points for measurements were set based on a preliminary survey of patients' behavior and led to a drastic change in ERDR. Time point 1 was set within the first 10min after the ^{18}F-FDG injection. Time point 2 was during the waiting period between the ^{18}F-FDG i.v. injection and the examination, before the first urine bladder emptying. Time point 3 was immediately after bladder emptying and time point 4 was immediately after the PET/CT or PET/MRI examination (Table 1).

Fluid intake before and after the ^{18}F-FDG injection, contrast agent dose, bladder emptying time between the ^{18}F-FDG injection and the PET/CT or PET/MRI examination, and after the PET/CT or PET/MRI examination were carefully recorded.

The ^{18}F-FDG dose was measured using a dose calibrator. The ^{18}F-FDG dose for PET/CT was determined based on the patient's general characteristics (Table 2). The minimum, average and maximum administered dosages were 296.00MBq, 439.93MBq, and 555.00MBq, respectively. (The recommended dosage for PET/CT at the hospital was 481MBq.) The ^{18}F-FDG dose for PET/MRI was determined based on patients' characteristics, with a minimum dosage of 173.16MBq, an average dosage of 226.44MBq, and maximum dosage of 320.05MBq (Fig. 1 and Table 2). (The recommended dosage for PET/MRI at the same hospital was 222.00MBq for adults.)

All 120 patients (60 PET/CT and 60 PET/MRI patients) gave their informed consent to be included in the study. The patients were admitted between August 2011 and April 2013 to a University Hospital in the Yeongnam region of Korea, where the first hybrid PET/MRI scanner had been installed and operated.

The measured data were analyzed by frequency and percentage, and are reported as the mean and standard deviation (mean±SD). Two-way and one-way analyses of variance (ANOVA), *t*-tests, and multiple regression analyses were performed using the SPSS statistical analysis software package.

Results

Results in Table 3 indicate statistical significant differences between time point and measurements at distances from the patient's body surface when the average ERDR for PET/CT and PET/MRI were compared. The ANOVA model was used to assess the correlation in more detail. Each group was divided into 11 subgroups, and two-way ANOVA was performed. For both PET/CT and PET/MRI, statistical significance was observed at the 1% significance threshold ($P<0.001$).

In Table 4 it is noteworthy that the ERDR significantly decreased over time for both PET/CT and PET/MRI measurements. The PET/CT results showed the highest concentration of ERDR (420.82±319.36μSvh^{-1}, $P<0.000$) at time point 1 in the chest area. However, at time points 3 and 4 the highest concentration of ERDR was 210.57±178.60μSvh^{-1} and 173.49±146.39μSvh^{-1}, respectively ($P<0.05$) and had shifted to the head region. Conversely, the PET/MRI results only showed the highest concentration of ERDR: 191.04±158.15μSvh^{-1}, $P<0.000$ at time point 1 at the chest area.

The results in Table 5 showed that for both PET/CT and PET/MRI the regression model did not fit time point 1. However, at time points 2, 3, and 4 where the regression analysis model was appropriate, the ^{18}F-FDG dosage was the predominant factor affecting ERDR. Therefore, using the minimum amount of ^{18}F-FDG necessary we could decrease the ERDR. Furthermore,

Table 1. *Time points for external radiation dose rate measurements*

Classification		PET/CT mean±SD (min)	PET/MRI mean±SD (min)
Time point 1	Within 10min after ^{18}F-FDG injection	4.17±4.62	6.73±5.79
Time point 2	Before the first urination and after ^{18}F-FDG injection	66.59±15.08	42.39±6.26
Time point 3	After the first urination and after ^{18}F-FDG injection	77.47±17.74	47.28±7.24
Time point 4	Immediately following the PET/CT or PET/MRI examination	114.15±18.46	136.11±25.64

Table 2. *General characteristics and dosage of the 120 subjects studied*

Characteristic	Classification	PET/CT n (%)	PET/MRI n (%)
Sex	Male	18 (30.0)	16 (26.7)
	Female	42 (70.0)	44 (73.3)
	Total	60 (100.0)	60 (100.0)
Age	Younger than 50y	27 (45.0)	13 (21.7)
	50y or older	33 (55.0)	47 (78.3)
Height	Shorter than 160cm	29 (48.3)	31 (51.7)
	160cm or taller	31 (51.7)	29 (48.3)
Body weight	Less than 60kg	27 (45.0)	30 (50.0)
	60kg or more	33 (55.0)	30 (50.0)
Body mass index (BMI, kg/m^2)	Underweight (BMI<18.5)	2 (3.3)	1 (1.7)
	Normal (18.5≤BMI≤24.9)	41 (68.3)	31 (51.7)
	Overweight (25.0≤BMI≤29.9)	16 (26.7)	13 (21.7)
	Obese (BMI≥30.0)	1 (1.7)	15 (25.0)
Diabetes mellitus	Present	9 (15.0)	4 (8.2)
	Absent	51 (85.0)	45 (91.8)
^{18}F-FDG dose (MBq)	Less than 481 in PET/CT and 222 or more in PET/MRI	36(60.0) 24(40.0)	31 (51.7) 29 (48.3)
Fasting time	Less than 10h	33 (55.0)	15 (25.0)
	10h or more	27 (45.0)	45 (75.0)
Fluid intake before admission	Less than 250mL	40 (66.7)	41 (70.7)
	250mL or more	20 (33.3)	17 (29.3)
Fluid intake after admission	Yes	20 (33.3)	1 (1.9)
	No	40 (66.7)	53 (98.1)
Number of urinations after ^{18}F-FDG injection	1	45 (75.0)	56 (93.3)
	2	14 (23.3)	4 (6.7)
	3 or more	1 (1.7)	0 (0.0)
Use of contrast agent	Yes	46 (76.7)	58 (98.3)
	No	14 (23.3)	2 (6.7)
	Total	60 (100.0)	60 (100.0)

**Missing data was reported on diabetes mellitus, fluid intake before admission, and fluid intake after admission.*
**The ^{18}F-FDG dosage was classified with a threshold of 481MBq for PET/CT and 222MBq for PET/MRI*

Table 3. *Relationships between the measurement time points and measurement distances*

	Source of	Sum of squares III type	Degrees of freedom	Mean square	F	P value
PET/CT	Adjusted model	44331079.888	11	4030098.172	597.769	0.000
	Intercept	27916741.330	1	27916741.330	4140.784	0.000
	Measurement time point	2447376.815	3	815792.272	121.003	0.000
	Measurement distance	36239702.499	2	18119851.250	2687.648	0.000
	Measurement time point × measurement distance	2638742.414	6	439790.402	65.232	0.000
	Error	10348813.589	1535	6741.898		
	Total	111455362.211	1547			
	Adjusted Total	54679893.477	1546			
PET/MRI	Adjusted model	10732643.320	11	975694.847	632.011	0.000
	Intercept	5467107.651	1	5467107.651	3541.345	0.000
	Measurement time point	475867.797	3	158622.599	102.749	0.000
	Measurement distance	8956542.745	2	4478271.373	2900.822	0.000
	Measurement time point × measurement distance	788697.328	6	131449.555	85.147	0.000
	Error	2034720.705	1318	1543.794		
	Total	24270210.387	1330			
	Adjusted Total	12767364.025	1329			

**Sum of squares of III type, the adjusted model and the intercept were used for the ANOVA modeling.*
**Setting of Type III sum-of-squares method is the default. This method calculates the sum of squares of an effect F in the design as the sum of squares adjusted for any other effects that do not contain it, and orthogonal to any effects (if any) that contain it. This type of sums of squares is often used for an unbalanced model with no missing cells. In a factorial design with no missing cells, this method is equivalent to the Yates' weighted squares of means technique, and it also coincides with the over parameterized ∑-restricted model. Sum of squares of III type in this study was used for the measurement time point variables and the measurement distance variables.*
**The intercept effect is treated as contained in all the pure factor effects.*

it was obvious that increasing fluid intake and the number of urinations, the patients' exposure to radiation and ERDR were decreased.

Discussion

It is impossible to change factors inherent to the patient, such as sex, age, height, body weight, obesity, and history of diabetes mellitus in order to decrease RE. However, factors that can be easily altered, such as fasting time, fluid intake before and after ^{18}F-FDG injection, number of urinations, and contrast agent dosage can minimize the external RE of the patients and of radiology-related healthcare workers and patients' guardians. Since the ^{18}F-FDG dosage most significantly affects the ERDR, it is important that the minimum dose for the patients' body weight must be used without affecting the image quality of the examination. Most of healthcare providers for their own convenience usually administer a standard dose of 481MBq for PET/CT and 222MBq for PET/MRI to all patients [26]. To limit patients' exposure to ionizing radiation, the minimum necessary dosage of ^{18}F-FDG should be individualized for every patient and the ^{18}F-FDG dosages must be based on the ICRP Principle of Justification [7-9]. However, guidelines for some ^{18}F-FDG PET studies in adults indicate high ERD, approximately 10mSv [5, 12, 13]. We consider that ERD must and can be lowered based on The Principle of Optimization of Protection and on the results of our study, which indicated the following intervention strategies: a) The minimum ^{18}F-FDG dose must be based on patients body weight. Fasting time should not be lengthened unnecessarily, and the minimum fasting time required for the examination should be used. b) The fluid intake of the patients and the number of urinations after the examination should be increased. c) If the purpose of the examination allows, PET/MRI should be chosen instead of PET/CT. d) If another person must approach a patient who has been administered ^{18}F-FDG, this person should remain as far as possible from the patient, or approach the patient from his feet region. This is both at time point 1 when the RE from the chest is significant and at time points 3 and 4 when the RE from the head region is significant. The above strategies can be implemented, considering that image resolution is not affected [27].

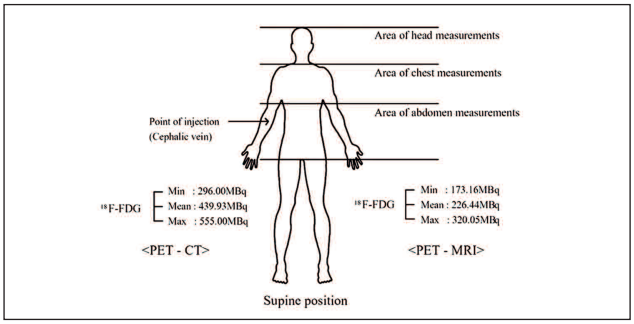

Figure 1. Diagram of patient measurement regions for PET/CT and PET/MRI. The mean of 3 measurements was used.

Table 4. *Changes in external radiation dose rate depending on the body region and distance*

Classification		Measurement time point 1 (4.17±4.62min) mean±SD (μSvh-1)	t, F,(p)	Measurement time point 2 (66.59±15.08min) mean±SD (μSvh-1)	t, F,(p)	Measurement time point 3 (77.47±17.74min) mean±SD (μSvh-1)	t, F,(p)	Measurement time point 4 (114.15±18.46min) mean±SD (μSvh-1)	t, F,(p)
PET/CT	Measurement distance 10cm	522.19±189.59	565.287 (0.000)	384.73±90.30	931.247 (0.000)	318.72±97.23	810.032 (0.000)	256.36±74.94	897.320 (0.000)
	Measurement distance 50cm	104.53±23.83		69.37±15.14		58.08±16.34		45.69±11.74	
	Measurement distance 100cm	39.75±13.75		28.31±10.28		19.82±8.87		12.90±3.18	
	Measurement region Head	222.34±150.38	21.720 (0.000)	223.69±178.65	0.633 (0.530)	210.57±178.60	3.026 (0.050)	173.49±146.39	3.337 (0.000)
	Measurement region Chest	420.82±319.36		213.99±146.55		190.61±135.95		142.16±98.53	
	Measurement region Abdomen	296.93±204.89		243.4±185.18		164.01±120.49		137.42±101.53	
	Measurement region Total	313.36±248.87		227.05±170.70		188.40±147.91		151.02±118.30	

Classification		Measurement time point 1 (6.73±5.79 min) mean±SD (μSvh-1)	t, F,(p)	Measurement time point 2 (42.39±6.26 min) mean±SD (μSvh-1)	t, F,(p)	Measurement time point 3 (47.28±7.24 min) mean±SD (μSvh-1)	t, F,(p)	Measurement time point 4 (136.11±25.64 min) mean±SD (μSvh-1)	t, F,(p)
PET/MRI	Measurement distance 10cm	258.76 ± 92.09	586.414 (0.000)	205.67±50.75	1169.735 (0.000)	179.31 ± 48.39	1011.776 (0.000)	105.63±27.48	1081.554 (0.000)
	Measurement distance 50cm	40.11±9.52		31.08±6.19		27.92 ±6.30		16.74±3.90	
	Measurement distance 100cm	3.62±1.50		3.16±1.31		2.60 ±1.21		1.51±0.69	
	Measurement region Head	103.92±75.51	12.143 (0.000)	104.62±83.43	1.473 (0.231)	98.87±79.31	1.887 (0.413)	62.50±51.43	0.060 (0.942)
	Measurement region Chest	191.04±158.15		124.31±98.40		112.86±90.82		60.08±46.73	
	Measurement region Abdomen	153.35±120.69		126.20±100.58		99.12±79.30		60.97±48.13	
	Measurement region Total	149.44±127.53		118.38±94.61		103.62±83.28		61.18±48.64	

***Table 5**. Factors that influence the external radiation dose rate of patients undergoing PET/CT and PET/MRI*

	Characteristic	Time point 1 (4.17±4.62min)		Time point 2 (66.59±15.08min)		Time point 3 (77.47±17.74min)		Time point 4 (114.15±18.46min)	
		β	t(P)	β	t(P)	β	t(P)	β	t(P)
PET/CT	(constant)		0.282 (0.779)		2.059 (0.049)		0.663 (0.511)		0.702 (0.486)
	Age	-0.126	-0.682 (0.499)	-0.534	-2.463 (0.020)	-0.199	-1.391 (0.171)	-0.114	-0.860 (0.394)
	Height	0.079	0.440 (0.662)	-0.258	-0.982 (0.335)	0.117	0.837 (0.407)	0.119	0.919 (0.363)
	Body weight	-0.275	-1.248 (0.218)	-0.329	-1.337 (0.192)	-0.432	-2.528 (0.015)	-0.350	-2.219 (0.031)
	^{18}F-FDG dose	0.348	1.468 (0.149)	0.108	0.313 (0.757)	0.589	3.202 (0.002)	0.546	3.218 (0.002)
	Fasting time	0.032	0.132 (0.896)	-0.053	-0.231 (0.819)	-0.115	-0.604 (0.549)	-0.109	-0.619 (0.539)
	Pre-admission fluid intake	0.027	0.148 (0.883)	-0.275	-1.153 (0.259)	0.008	0.054 (0.957)	-0.098	-0.761 (0.451)
	Post-admission fluid intake	-0.112	-0.487 (0.628)	0.084	0.342 (0.735)	-0.134	-0.751 (0.457)	-0.304	-1.842 (0.072)
	Contrast agent dose	0.080	0.373 (0.711)	0.156	0.482 (0.634)	0.372	2.241 (0.030)	0.340	2.216 (0.032)
	Number of urinations	-0.044	-0.232 (0.818)	-	-	-0.343	-2.308 (0.025)	-0.445	-3.243 (0.002)
	F(p-value)	0.549 (0.831)		2.327 (0.048)		4.362 (0.000)		6.019 (0.000)	
		0.095		0.408		0.455		0.535	

	Characteristic	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)
PET/MRI	(constant)		1.519 (0.131)		4.520 (0.000)		2.540 (0.012)		-1.176 (0.242)
	Age	-0.050	-0.490 (0.625)	-0.153	-1.996 (0.048)	-0.103	-1.390 (0.167)	-0.118	-0.218 (0.828)
	Height	-0.036	-0.288 (0.774)	-0.244	-2.591 (0.011)	-0.106	1.192 (0.236)	0.279	2.791 (0.006)
	Body weight	-0.125	-0.837 (0.404)	-0.093	-0.832 (0.407)	-0.163	-1.520 (0.131)	-0.227	-1.889 (0.061)
	^{18}F-FDG dose	0.286	2.639 (0.009)	0.568	7.006 (0.000)	0.637	8.206 (0.000)	0.463	5.330 (0.000)
	Fasting time	0.037	0.386 (0.700)	0.029	0.413 (0.681)	0.020	0.287 (0.775)	0.306	4.005 (0.000)
	Pre-admission fluid intake	0.023	0.234 (0.815)	0.003	0.043 (0.965)	0.034	0.479 (0.633)	0.004	0.053 (0.958)
	Post-admission fluid intake	-0.102	-1.051 (0.296)	-0.005	-0.072 (0.943)	-0.052	-0.744 (0.458)	-0.037	-0.479 (0.633)
	Fluid intake	0.018	0.188 (0851)	0.145	-2.016 (0.046)	-0.174	-2.555 (0.012)	-0.156	-2.053 (0.042)
	Number of urinations	-0.063	-0.643 (0.552)	-0.181	-2.450 (0.016)	-0.143	-2.024 (0.045)	0.009	0.111 (0.912)
	Contrast agent dose	-0.039	-0.327 (0.744)	-0.057	-0.619 (0.537)	0.039	0.459 (0.647)	-0.159	-1.649 (0.102)
	F(p-value)	1.547 (0.132)		12.088 (0.000)		13.905 (0.000)		8.778 (0.000)	
		0.119		0.526		0.547		0.433	

**The number of urinations had an error with a missing correlation coefficient at time point 2 of the PET/CT data, and was therefore excluded as an independent variable. Beta are the predictable physical characteristics of the patients. P-value was based on t-test.*
**A multiple linear regression analysis was performed to determine the factors affecting the ERDR on patients undergoing PET/CT and PET/MRI using the ERDR as the dependent variable and using age, height, body weight, ^{18}F-FDG dose, fasting time, fluid intake before admission, fluid intake after admission, contrast agent dose, and number of urinations as independent variables.*

Previous studies including IAEA and NRC studies have reported similar results using distance and time as influencing factors. However, this study in Korea is the first to include additional variables, like fasting time, body height and weight fluid intake etc. [28-32].

In conclusion, our results indicated that: the ERDosage from PET/CT is about twice higher compared to that from PET/MRI and that the minimum administered ^{18}F-FDG dosage must be based on the patient's body weight, the minimum fasting time, the fluid intake of the patients and urine bladder emptying after the examination. All persons should keep a safe distance from the injected patient.

The authors declare that they have no conflicts of interest.

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