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Relationship between Patient-Dependent Parameters and Radiation Dose Rates Measured around Patients Undergoing PET/CT Imaging Using ^{18}F-FDG

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Abstract

Objectives: Patients undergoing ^{18}F-FDG PET/CT imaging are considered external radiation sources. Accurate dose rate estimates are important for conducting realistic risk assessments and performing dose reconstruction in cases of accidental exposures. The patient radiation self-attenuation factor is assumed to be a function of the patient's body size metrics, but we can use these metrics to predict the dose rate around the patients with accuracy. The objective of this work was first to measure the patient attenuation factor by performing direct dose rate measurements from patients undergoing PET/CT imaging studies using ^{18}F-FDG. The second objective was to study the possible correlation between the measured dose rate constant per unit activity from the patients and their body size metrics; five metrics were tested in this work. The last objective was to measure the patients' voiding factor. **Methods**: We have measured dose rates at one meter from 57 patients and noted the patient's height (H), weight (W) and calculated patient size metrics namely: Equivalent Cylindrical Diameter (ECD), Equivalent Spherical Diameter (ESD) and the Body Mass Index (BMI). **Results**: The measured average dose rate was 92.2 ± 14 $\mu\text{Sv}\cdot\text{h}^{-1}\cdot\text{GBq}^{-1}$ measured at one meter. Therefore, the dose rate constant of 92 $\mu\text{Sv}\cdot\text{h}^{-1}\cdot\text{GBq}^{-1}$ proposed by the AAPM, TG-108 report is adequate for radiation protection purposes. There was no statistically significant correlation between the dose rate constant per unit activity and the patient body size metrics. We have measured a patient voiding factor of 0.89 ± 0.06 in comparison with 0.85 recommended by the AAPM. **Conclusions**: The presented data can be used by medical physicist working in nuclear medicine in formulating more accurate risk estimations resulting from radiation exposure from patients undergoing ^{18}F-FDG PET/CT imaging.

Keywords

FDG, Measured Dose Rate, Patient Voiding Factor, Patient Attenuation Factor, Patient Size

1. Introduction

The estimated dose rate at certain distance from a radioactive source depends on the dose rate constant, the source activity and the distance between the source and the measurement point. Once the radioactivity is incorporated into the patient, it will additionally depend on his body tissues attenuation properties.

Accurate dose rate estimates are important for radiation protection specialists conducting risk assessments and performing dose reconstruction in cases of accidental exposures. The American association of physicist in medicine (AAPM) in their report TG-108 shielding design for positron emitted tomography/computed tomography (PET/CT) imaging facilities recommends the use of a dose rate constant of 92 µSv/h/GBq for Fluorine-18 based compounds in situation where the patient is considered the source of radiation exposure [1]. The value proposed by the AAPM is used in the calculations of the facility shielding design, where significant cost savings are achieved by using optimized designs while eliminating the use of additional shielding materials thicknesses. In the same AAPM report, it is also suggested to use a patient voiding factor of 0.85 in order to take into account the decrease in the total injected radioactivity due to voiding before imaging the patients in general.

The objectives of this work were first to experimentally measure the patient's body attenuation effect by performing direct dose rate measurements from patients undergoing PET/CT imaging studies using fluorodeoxyglucose ^{18}F (FDG) and to compare the measurements with the reported air kerma rate constant proposed in the AAPM report, reported to be equal to 134 µSv/h/GBq. The second objective was to quantify the effect of patients' bladder emptying on the measured dose rate values measured from the patients before and after voiding; and the last objective was to examine the effect of patients' body sizes metrics on the measured dose rates by performing statistical analysis using linear correlation methods. The aim of finding a correlation between the body size metrics and the measured dose rate per unit activity is to be able to predict with enough accuracy the dose rates around the patients in situations where actual dose rate measurements are not possible. Incident reconstruction scenarios are examples of situations, are accurate dose predictions and will help in putting the risk from radiation exposure in proper perspective.

2. Materials and Methods

2.1. Measured dose Rate per Unit Activity

The measured dose rate at voiding time divided by the activity calculated at the voiding time and corrected for radioactive decay was used for each patient to calculate the dose rate per unit activity constant and to compare it with the AAPM TG-108 proposed patient dose rate constant (G) of 92 μSv·m^2/h/GBq. the dose rate from the patient is given by the following equation:

$$D_P / A = GC_dC_{PA} \tag{1}$$

where C_d: is the distance correction factor or the inverse square law correction factor depending on the radiation source model, point or line source. In this work, we have measured the dose rate at 1 m and C_d was assumed to be equal to 1;

C_{PA}: is the patient attenuation correction factor;

D_p/A: is the measured dose rate per unit activity.

Radiation dose measurements were done immediately before and after voiding, in order to calculate the dose rate reduction factor using equation 4 below. We have excluded from this analysis the patients with measured dose rate after voiding that were slightly higher than before voiding due to some mild urine contamination on their cloth. The total number of patients measurements reported in this study is 57, details are in Table 1.

The radiation dose rate was measured using a calibrated ionization chamber (SmartIon Type: 2120G; thermo Franklin, Massachusetts, USA). The FDG dose was administered using an automatic dose injector (Intego, by MedRad Inc, Indianola, PA, USA).

2.2. Correction for Uptake Time

The activity measured at the uptake time was calculated using the following relation:

Table 1. Patients data used in this study.

Parameter	Average ± SD (min-max)
Total number of patients	57
Male	27
Female	30
Age range in [years]	22 - 79
Weight (W) in [kg]	77 ± 26 (53 - 171)
Equivalent cylindrical diameter (ECD) in [cm]	17 ± 3 (9 - 11)
Equivalent spherical diameter (ESD) in [cm]	25 ± 3 (15 - 33)
Body mass index (BMI)	29 ± 8 (11 - 58)
Ratio of Weight/Height (W/H) in [kg/m]	47 ± 14 (13 - 99)
Uptake time in [minutes]	39 ± 8 (17 - 68)
patient voiding factor	0.89 ± 0.06 (0.70 - 0.98)
Voiding %	11% ± 6% (2% - 30%)
Dose rate per unit activity in μSv/h/GBq	92.2 ± 14 (65 - 136)

$$A\left(t_{up}\right) = A_0 e^{-\lambda t_{up}} \tag{2}$$

where t_{up}: is the uptake time in minutes, and λ: is equal to $\ln(2)/T_{1/2}$.

$T_{1/2}$ is the half-life of ^{18}F = 110 minutes.

2.3. Dose Rate Reduction due to Voiding

We have calculated the patient voiding factor (R) as the ratio of the dose rate measured after voiding over the dose rate measured before voiding:

$$R = D_{\text{after}}/D_{\text{before}} \tag{3}$$

The percentage of dose reduction due to voiding is then given by:

$$D_{\text{reduction}}(\%) = (1-R)*100\% \tag{4}$$

2.4. Patient Body Density

We have used a patient body density value of 1 g/cm^3 same to that of water as an acceptable assumption in this study.

2.5. Equivalent Cylindrical Diameter (ECD)

The volume (V) of a cylinder with radius (r) and simulating the patient with height (H) is given by:

$$V\left[\text{cm}^3\right] = 2\pi r^2 H \tag{5}$$

$$V\left[\text{cm}^3\right] = M/\rho,\ \rho \text{ in } [\text{g}\cdot\text{cm}^{-3}],\ M \text{ is the mass in } [\text{g}] \text{ and } H \text{ in } [\text{cm}]. \tag{6}$$

By Combining (4) and (5), we can calculate the cylindrical radius to be equal to:

$$r = \left[(M/\rho)/2\pi H\right]^{1/2} \tag{7}$$

where, ρ is the density of water and equal to 1 [g·cm^{-3}].

2.6. Equivalent Spherical Radius (ESR)

The volume of a sphere made of water and simulating a patient is given by:

$$V = 4/3\,\pi r^3 \tag{8}$$

$$V\left[\text{cm}^3\right] = M/\rho,\quad \rho \text{ in } [\text{g}\cdot\text{cm}^{-3}] \text{ and } M \text{ in } [\text{g}] \tag{9}$$

$$r^3 = 3M/4\pi\rho,\ r = (3M/4\pi\rho)^{1/3}$$

With ρ equal to the density of water: 1 [g·cm^{-3}]; the spherical radius is then will be equal to:

$$r = (3M/4\pi)^{1/3} \tag{10}$$

This work was approved by the hospital medical research ethics committee.

2.7. Statistical Analysis

Pearson's r correlation coefficient between the patient physical parameters and the dose rate measured were calculated using MATLAB Statistical Toolbox ver. 7.12. r, r^2 and p values are given for each physical parameter assessed.

The most significant parameter that may affect the dose rate was identified as the body mass index (BMI). All other tested parameters had statistical significant value above 99%, *p* values was less than 0.001 for all of the calculated patient's physical parameters assessed.

3. Results

3.1. Patient self-Attenuation Factor

We have measured the dose rate at one meter from the patient entrance body surface in the anterior direction. We have divided the measured dose rate per the injected activity to obtain a constant value of 92.2 with a standard deviation of 14, a maximum value of 136 and a minimum of 65 (μSv/h/GBq); details are in Table 1. Our results are in close agreement with the recommended value of 92 (μSv/h/GBq) by the AAPM, TG-108 report.

3.2. Effect of Voiding on the Measured dose Rate

We have calculated the ratio of the dose rates measured after voiding to before voiding in order to present the results as percentage of the released activity due to voiding and to compare our measurements to the published data regarding the percentage of activity excreted by the patient due to voiding. The amount of voided activity will contribute to the dose reduction in the bladder of the patient (Hays *et al.*, 1998) [2].

We have quantified the effect of voiding on the measured dose rate from the patients and found it to reduce the dose rate by 11%. The literature reports reduction in the order of 15% of the injected activity for the first 2 hours post injection of the FDG [3]. We have found a wide variation for the first void time, our average time measured before the first void was 39 ± 8 minutes; other studies reports different values; 83 ± 19 minutes and 77 ± 18 minutes [4] [5] [6].

It is also worth to mention that we have excluded certain number of patient data from our study because the measured dose rate after voiding was higher than the one measured before. We concluded that these patients had accidentally contaminated their cloth with radioactive urine during voiding, which caused the dose rate after voiding to be higher.

3.3. Correlation of Patient's Body Metrics and the Measured dose Rate

We have used five metrics to represent the patient size, the patient body weight (W) in [kg], the body mass index (BMI) in [kg/m^2], the ratio of patient weight to height (W/H) in [kg/m], the equivalent cylindrical diameter (ECD) in [cm], which is a cylinder full of water and having the same weight and height as the patient given by (Equation (6)) and the equivalent spherical radius (ESR) in [cm],which is a sphere made of water having the same mass as the patient given by (Equation (9)).

We have measured the strength of the association between the dose rates per unit activity and the patient body size metrics using statistical parameters: the coefficient of correlation (r), the coefficient of determination (r^2) and the significance level (p) value. MATLAB statistics toolbox ver. 7.12.0 was used to perform the statistical analysis.

For all of the 57 patients, the measured dose rate per unit activity in [μSv/h/GBq] as a function of the patients' body size metrics were plotted as shown in (Figures 1-5).

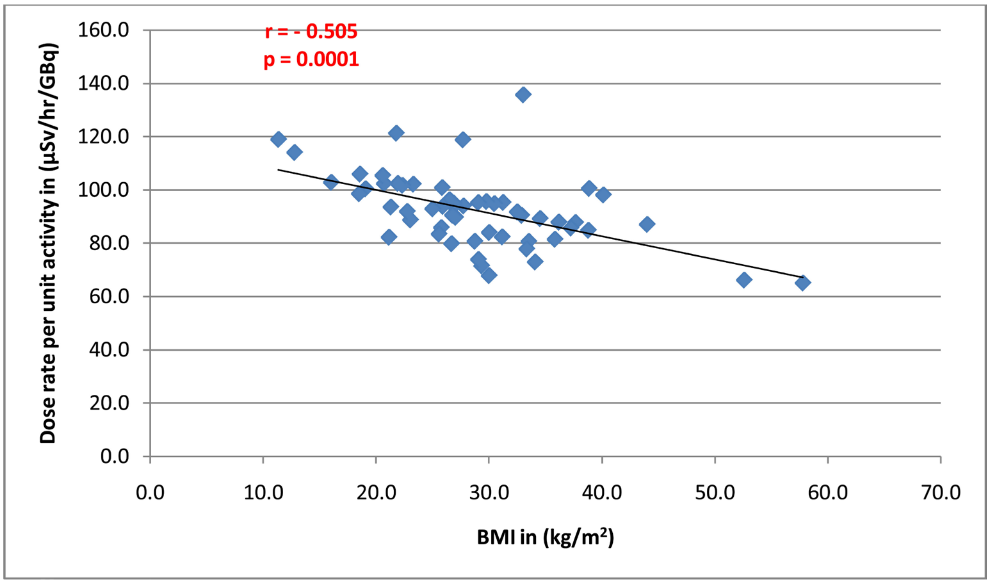

Figure 1. Graph of the measured dose rate per unit activity in (μSv/h/GBq) as a function of the patient body mass index (BMI). We notice the negative slope of the trend line indicating that when the patient BMI increases the dose rate per unit activity decrease due to attenuation of the radiation by the patient body.

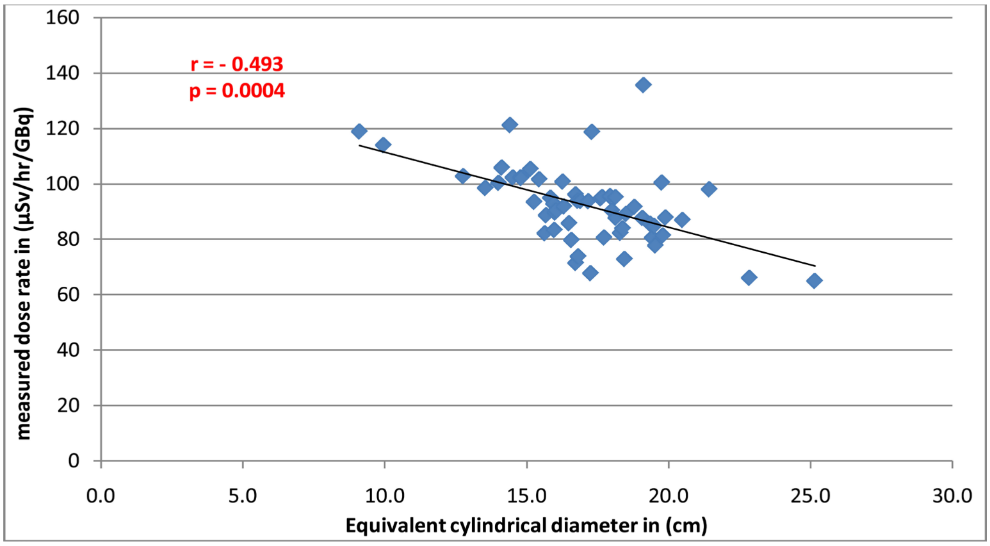

Figure 2. Graph of the measured dose rate per unit activity in (μSv/h/GBq) as a function of the patient equivalent cylindrical diameter (ECD). We notice the negative slope of the trend line indicating that when the patient ECD increases the dose rate per unit activity decrease due to attenuation of the radiation by the patient body.

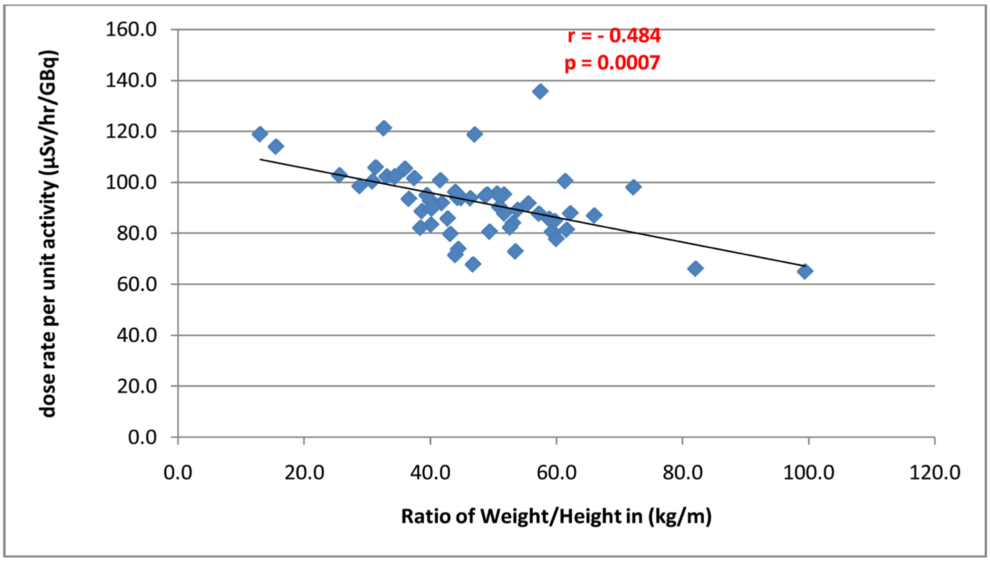

Figure 3. Graph of the measured dose rate per unit activity in (μSv/h/GBq) as function of the ratio of the patient weight to the patient height (W/H). We notice the negative slope of the trend line indicating that when W/H increases the dose rate per unit activity decrease due to attenuation of the radiation by the patient body.

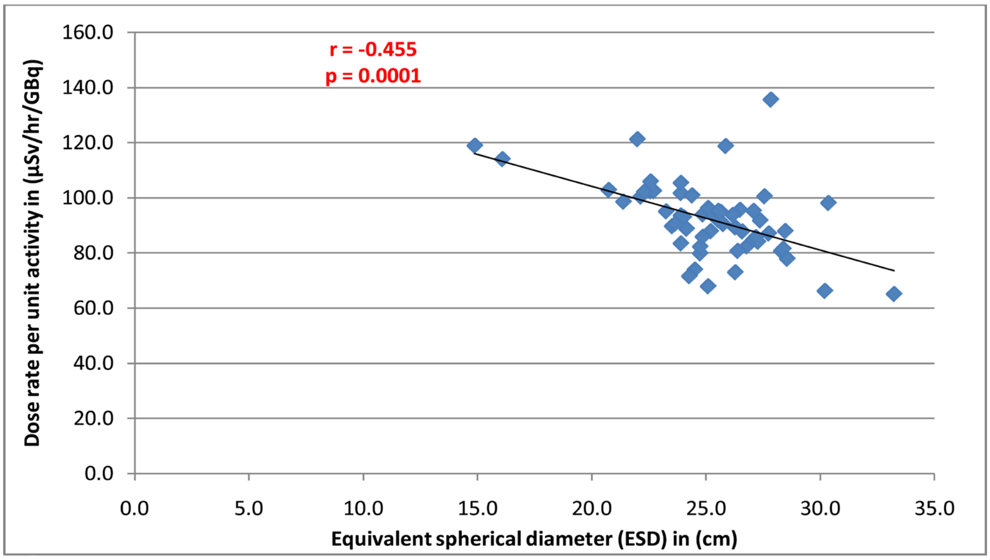

Figure 4. Graph of the measured dose rate per unit activity in (μSv/h/GBq) as a function of the patient equivalent spherical diameter (ESD). We notice the negative slope of the trend line indicating that when the patient ESD increases the dose rate per unit activity decrease due to attenuation of the radiation by the patient body.

We have obtained a weak correlation ($r < 0.51$, $p < 0.001$) between the measured dose rate constant and the patient body size parameters (BMI, ECD, W/H, ESD and W). With the BMI having the strongest correlation coefficient at ($r = -0.505$, $p = 0.0001$). The negative correlation coefficients means when the patient size metrics increase the dose rate from the patient decrease which is normally due to the patient body attenuation factor that reduces the measured dose rate form the radiation sources distributed inside the patient body organs (Table 2).

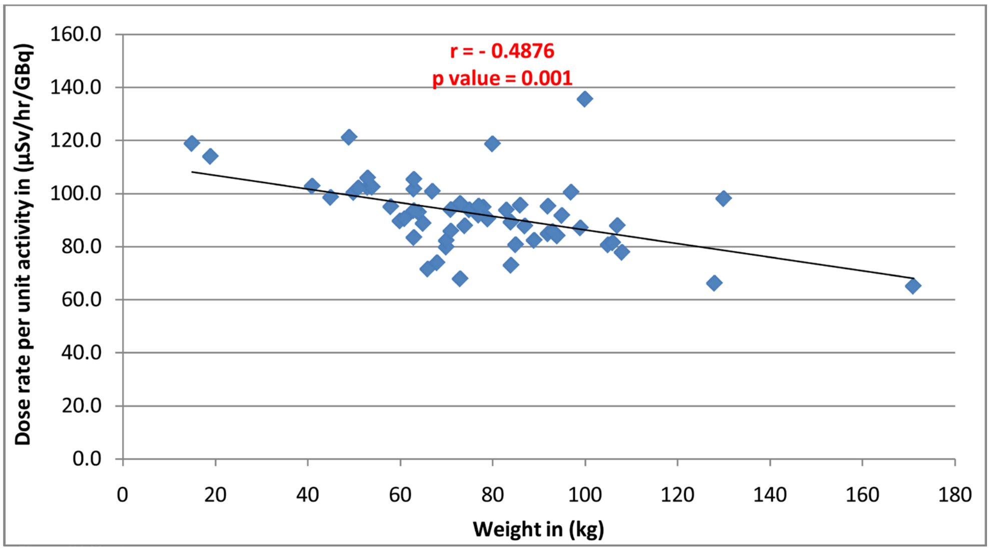

Figure 5. Graph of the measured dose rate per unit activity in (µSv/h/GBq) as a function of the patient weight (W). We notice the negative slope of the trend line indicating that when the patient weight increases the dose rate per unit activity decrease due to attenuation of the radiation by the patient body.

Table 2. Correlation parameter between the patient physical data parameters and the dose rate measured from the patient at one meter. r, r^2 and p values are given for each parameter in decreasing order.

Parameter	r	r^2	p
Body Mass Index [BMI]	−0.505	0.255	0.0001
Equivalent Cylindrical Diameter [ECD]	−0.493	0.243	0.0004
Weight/Height ratio [W/H]	−0.484	0.235	0.0007
Equivalent Spherical Diameter [ESD]	−0.455	0.207	0.0001
Weight [W]	−0.442	0.195	0.0002

The most significant parameter that may affect the dose rate is the body mass index (BMI). All tested parameters had statistical significant value above 99%, p values was less than 0.001.

Because of the strong heterogeneity of the radioactive material (the FDG) distribution inside the patient body it was very difficult to predict the external radiation dose rate measured at one meter from the patient by using only the patient body size metrics and the injected activity. Therefore we conclude that it is not possible to accurately estimate the radiation dose rate at one meter from the patient without performing actual radiation dose measurements.

4. Discussion

As patient weight increases, fewer photons are getting out of the body [7]. High photon attenuation and scatter in obese patients affect image quality [8] [9]. Masuda *et al.*, 2009 [10] demonstrated that the quality of 18F-FDG PET/CT images of overweight patients is often degraded. This fact is apparently due to the patient self-shielding effect.

Self-attenuation of radiation by patient's bodies was quantified, and found to cause a significant decrease in radiation exposure of more than 40% due to non-uniform distribution of FDG and attenuation within the patients [11].

Quinn *et al.*, 2012 [12] support the use of 0.092 µSv/hr/MBq measured at 1 meter from the chest of patients immediately following injection or 0.067 at 60 min post injection as reasonable representation of the dose rate.

Yi *et al.*, 2013 [13] have compared the measured and calculated dose rates from the radioactive patient and found that the calculated values were always higher than measured values and suggested the application of self-shielding factors.

In most cases the patient will void prior to imaging, removing approximately 15% - 20% of the administered activity and thereby decreasing the dose rate by 0.85 [1]. The initial voiding time seems to play a role in the dose calculations to the bladder wall; the optimum initial voiding time to deliver the lowest dose according to the traditional MIRD static bladder model is 40 minutes [14].

PET image quality depends on patient weight and habitus; decreasing image quality is associated with an increasing weight and body mass index [15]. It was proposed that ^{18}F-FDG dose injected should be adjusted to both body weight and height [6]. Cylindrical phantoms have been used to simulate patients with different body masses in order to optimize the FDG dose regime for imaging studies [16].

5. Conclusions

The measured dose rate per unit on injected activity in this study was in agreement with the recommended value by the AAPM TG-108. Patient bladder voiding before scanning reduced the measured dose rate at one meter from the patient by about 11%. Finally, patient body size metrics cannot be used solely to predict the dose rate levels expected from individual patient without performing actual radiation dose rate measurements.

The activity normalized dose rate constant of 92 (µSv/h/GBq) measured at one meter anterior to the patient can be used with confidence to estimate dose rates from patients undergoing PET/CT imaging using FDG, because it includes patient body attenuation and scatter factor.

The presented information will benefit medical physicist working in nuclear medicine, radiation safety policy makers and regulators.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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