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Derivation of the scan time requirement for maintaining a consistent PET image quality

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ABSTRACT: *Objectives*: the image quality of PET for larger patients is relatively poor, even though the injection dose is optimized considering the NECR characteristics of the PET scanner. This poor image quality is due to the lower level of maximum NECR that can be achieved in these large patients. The aim of this study was to optimize the PET scan time to obtain a consistent PET image quality regardless of the body size, based on the relationship between the patient specific NECR (pNECR) and body weight.

Methods: eighty patients (M/F = 53/27, body weight: 59 ± 10 kg) underwent whole-body FDG PET scans using a Philips GEMINI GS PET/CT scanner after an injection of 0.14 mCi/kg FDG. The relationship between the scatter fraction (SF) and body weight was determined by repeated Monte Carlo simulations using a NEMA scatter phantom, the size of which varied according to the relationship between the abdominal circumference and body weight. Using this information, the pNECR was calculated from the prompt and delayed PET sinograms to obtain the prediction equation of NECR vs. body weight. The time scaling factor (F_{TS}) for the scan duration was finally derived to make PET images with equivalent SNR levels.

Results: the SF and NECR had the following nonlinear relationships with the body weight: $SF = 0.15 \cdot \text{body weight}^{0.3}$ and $NECR = 421.36\ (\text{body weight})^{-0.84}$. The equation derived for F_{TS} was $0.01 \cdot \text{body weight} + 0.2$, which means that, for example, a 120-kg person should be scanned 1.8 times longer than a 70 kg person, or the scan time for a 40-kg person can be reduced by 30%.

Conclusion: the equation of the relative time demand derived in this study will be useful for maintaining consistent PET image quality in clinics.

KEYWORDS: Data processing methods; Gamma camera, SPECT, PET PET/CT, coronary CT angiography (CTA)

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1 Introduction

F-18 FDG PET imaging is a noninvasive diagnostic tool widely used in clinics in the field of nuclear medicine. Dose determination of FDG is important to improve and to get consistency of image quality. The strategy for dose determination was investigated by many researchers for a long time. Basically, NEMA NU2-2007 guide line provided the optimal range of injection dose using calculation of noise equivalent count rate (NECR) [1–3]. 200 MBq of FDG was reported as an optimal dose for a 3D brain acquisition using the calculation of NECR [4]. Optimal injected dose based on NECR for 2D and 3D whole body PET was reported [5]. Optimal injected dose in clinical PET was modeled using the count rate response functions specific to individual patient scans. For an equivalent data SNR, a 120-kg person would have to be scanned 2.3 times longer than a 60-kg person [6]. The quality of FDG PET images of overweight patients was degraded [7]. Poorer image quality of PET was consistently generated with patients with larger body mass index (BMI) [8]. Poorer image quality of PET for obese patients was due to high photon attenuation and scatter in obese patient. Scans with 5 minute acquisitions per bed position were recommended for lesion detectability and reader concordance in obese patients weighing $\geqq$ 91 kg (200 lb) with LSO PET/CT [9]. There was a report for the relation between dose and scan time for improving image quality. Masuda and colleagues reported that increasing the dose per kilogram of body weight did not improve the quality of PET images. The quality of PET images acquired from heavier patients could be maintained only by scanning for longer periods [7]. Dose optimization was also important for pediatric patients. According to the Alessio and colleagues report's, 5.3 MBq/kg of weight based injected activity and 3–5 min/field of view of acquisition times were optimal protocol which was also confirmed with estimated dosimetry [10].

In this present study, we developed the scan time requirement for maintaining a consistent PET image quality using Monte Carlo simulation based patient specific NECR (pNECR). Our

Table 1. Body weight and injected dose.

Body weight (kg)	Recommended injected dose (mCi) *	Calculated optimal dose (mCi) †
22	3.08	5.26
30	4.20	7.17
40	5.60	9.56
50	7.00	11.95
60	8.40	14.34
70	9.80	16.72
80	11.20	19.11
90	12.60	21.50
100	14.00	23.89

* Injected dose was 0.14 mCi/kg. This value was recommended by Philips medical systems.

† Calculated optimal dose was 0.24 mCi/kg. This value was calculated according to NEMA NU2-2001 standards.

suggested method provided time scaling factor for the consistency of PET image quality. The relationship between NECR and multiple parameters such as skeletal muscle mass, total protein amount, mineral mass, body fat percentage for individual subjects was also assessed.

2 Materials and methods

2.1 Data acquisition

Eighty patients (M/F = 53/27, weight: 59 ± 10 kg) underwent whole-body FDG PET scans using a Philips GEMINI GS PET/CT scanner after injection of 0.14 mCi/kg FDG recommended by the vendor. Table 1 shows that body weight and injected dose in our present study. Based on NECR calculation according to NEMA NU2 guidelines, calculated optimal dose was 0.24 mCi/kg [11]. Optimal dose for patients recommended by manufacturer corresponds to 56% of peak NECR level measured using NEMA NU2 guideline. The energy window was 409–665 keV. The coincidence window was 8 ns. The PET scan time was 90 sec per bed. For whole body PET acquisition, the PET data was acquired in 7–9 beds. The body weight, height, and abdominal circumference of each patient were also measured. The abdominal circumference and body weight of 185 subjects were measured to derive the relationship between the abdominal circumference and body weight. In this study all analyses were performed retrospectively on anonymized clinical patient data. Therefore, approval by the medical ethics committee was not required. Multiple parameters such as skeletal muscle mass, total protein amount, mineral mass, body fat percentage for individual subjects were measured.

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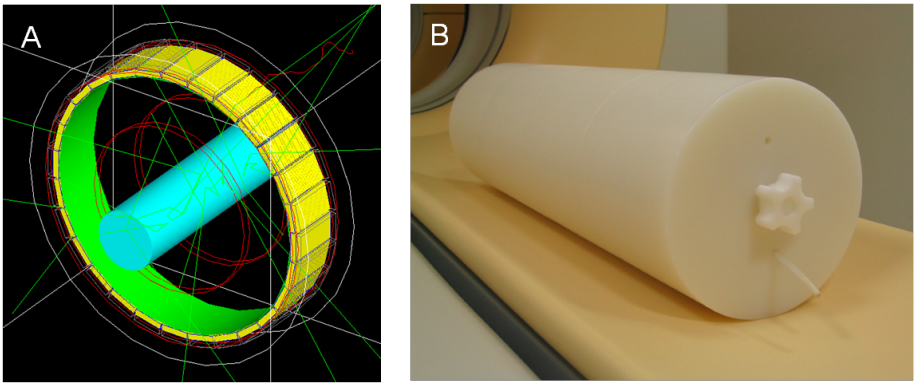

Figure 1. (A) Schematic of the Monte Carlo simulation for the measurement of scatter fraction and (B) scatter fraction phantom according to the NEMA NU2-2007 guidelines.

2.2 Scatter fraction versus the body weight

Conventionally, the scatter fraction was measured using the NEMA scatter phantom recommended by the NEMA NU2-2007 [1]. In the NEMA NU2-2007 standard, the scatter fraction phantom was 70 cm in length and 20 cm in diameter. This corresponds to a 22 kg sized human body. The PET injection dose was determined based on the measurement of the count rates and NECR according to NEMA NU2-2007. Nevertheless, the scatter fraction from the measurement according to the NEMA standards could not be applied to real PET data because the photon scatter and attenuation would be not the same as the scatter fraction measured using the phantom [6]. In Watson's method [6], the scatter fraction was derived from the individual PET data. The pNECR was derived from the individual PET sinogram. In this study, the scatter fraction was calculated with various body weights (ranged 30 kg to 120 kg in steps of 10 kg) using a Monte Carlo simulation. Monte Carlo simulation code was validated in previous study [12]. Simulated [12] and experimental results [11] for the calculation of scatter fraction was well matched. The scatter fraction was 40.6% for the simulated study and 40.9% for the experimental result, respectively (figure 1) [11, 12]. The radius of the simulated scatter phantom corresponding to a particular scatter fraction was then determined from the relationship between the body weight and abdominal circumference which was derived from the data of the 265 subjects. The scatter fraction was calculated based on actual sized phantom determined relationship between the body weight and abdominal circumference. The Monte Carlo simulation was performed repeatedly to calculate the scatter fraction with various sizes based on the derived relationship between the body weight and abdominal circumference Finally, the relationship between the body weight and scatter fraction was derived.

2.3 Patient specific NECR

To calculate the pNECR, the prompt and delayed count rate was extracted from the sinogram data of each patient. The true and scatter count rate was calculated using the scatter fraction, which corresponded to the each patient's body weight. The pNECR was then calculated for each bed position. The mean pNECR was then calculated by averaging the pNECR from the pNECR at every bed position. The following equation for the pNECR was obtained.

$$\mathrm{pNECR} = \mathrm{T}^2/(\mathrm{T}+\mathrm{S}+\mathrm{R})\,. \tag{2.1}$$

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In this equation, T is the true count rate, S is the scatter count rate and R is the random count rate. The relationship of pNECR and multiple parameters including skeletal muscle mass, total protein amount, mineral mass, and body fat percentage for individual subjects was calculated.

2.4 Derivation of time scaling factor

The NECR is related to the SNR [13]. The relationship between the NECR and SNR is assumed as follows:

$$\mathrm{SNR}^2 = \mathrm{NECR} \times \Delta t\,. \tag{2.2}$$

In PET scanning, Δt means the scan time duration. In this study, a scan time duration of 90 sec per bed was used for PET imaging, irrespective of the patient's size. The methods for improving the SNR of PET were to increase the injection dose to the optimal dose or to lengthen the scan time. The injection dose could be increased up to optimal dose. The SNR could be improved by increasing the injection dose because the calculated optimal dose in GEMINI GS PET/CT was 0.24 mCi/kg which was calculated based on NECR measurements [11]. However, this study focused on the relationship between the NECR and PET scan time when the injection dose was fixed to avoid radiation hazard from the increased injection dose. The other method for improving SNR of PET was to lengthen the scan time. To determine the scan time, a scaling factor ($\mathrm{F_{TS}}$) for the scan duration was derived to produce PET images with SNR levels using equation (2.3). To determine the $\mathrm{F_{TS}}$ scan time duration for a 70 kg-person was used as standard. Additionally, a time scaling factor was also derived using the relationship between pNECR and BMI.

$$\text{Time scaling factor } (\mathrm{F_{TS}}) = \text{pNECR for 70 kg-person}/\text{pNECR for individual patient}\,. \tag{2.3}$$

3 Results

Figure 2 shows the representative PET images with lighter patients (weight: 48 kg and BMI: 18.35) and heavier patients (weight: 89.3 kg and BMI: 27.26) in our present study. We found that the uniformity of lighter patients was degraded compared to that of heavier patients, especially in lung lesions. This result was in accordance with previous findings [9].

Figure 3 shows a plot of abdominal circumference and body weight. From this data, the relationship between abdominal circumference and body weight was derived ($\mathrm{R}^2 = 0.67$).

$$\text{Abdominal circumference } = 0.10\ (\text{body weight}) + 66.35\,. \tag{3.1}$$

Table 2 shows the radius for calculation of scatter fraction in Monte Carlo simulation based on the derived equation between body weight and abdominal circumference.

Figure 4 shows the representative figures for the 50, 70 and 90 kg phantoms. Simulated result of the scatter fraction was 47.6, 53.0 and 59.9%, respectively. The scatter fraction for various phantoms (30–120 kg) was calculated using a Monte Carlo simulation. The relationship between the body weight and scatter fraction was derived ($\mathrm{R}^2 = 0.96$).

$$\mathrm{SF} = 15.5\ (\text{body weight})^{0.3}\,. \tag{3.2}$$

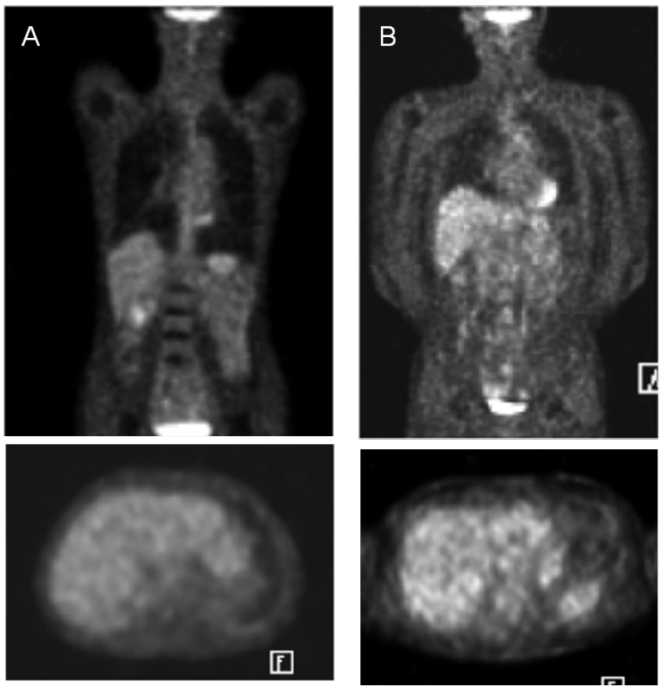

Figure 2. A representative PET image with (A) lighter patients (body weight: 48 kg and BMI: 18.35) and (B) heavier patients (body weight: 89.3 kg and BMI: 27.26) in our present study. We could find that the uniformity of lighter patients was degraded compared to that of heavier patients especially in lung lesion.

Table 2. The radius for simulation of scatter fraction.

Body weight (kg)	Radius (cm)
30	9.6
40	10.7
50	11.8
60	12.9
70	13.9
80	15.0
90	16.1
100	17.2
110	18.2
120	19.3

Figure 5(A) shows a plot of the pNECR and body weight ($R^2 = 0.71$). Figure 5(B) shows a plot of the pNECR and BMI ($R^2 = 0.63$). The following relationships were as follows

$$\text{pNECR} = 421.36\ (\text{body weight})^{-0.84}. \tag{3.3}$$

The relationship of NECR and multiple parameters including skeletal muscle mass, total protein amount, mineral mass, body fat percentage for individual subjects was poorly correlated. The

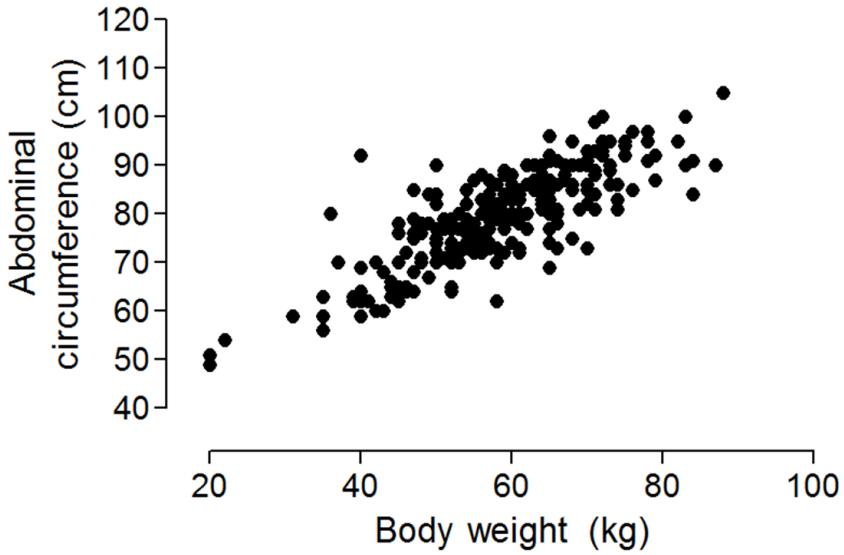

Figure 3. Plot of the abdominal circumference versus body weight. From this data, the relationship between abdominal circumference and body weight was derived as follows: abdominal circumference = 0.10 (body weight) +66.35.

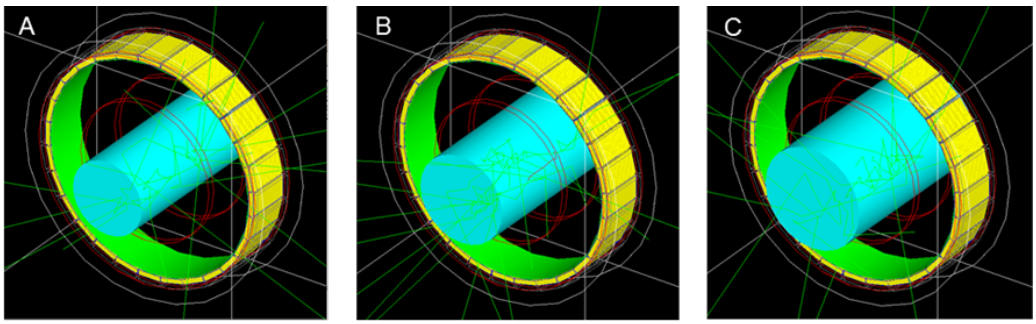

Figure 4. The representative figures for the (A) 50, (B) 70 and (C) 90 kg phantom using the Monte Carlo simulation. The radius of phantom was determined based on relationship between abdominal circumference and body weight.

R^2 was 0.56 for skeletal muscle mass, 0.54 for mineral mass, and 0.46 for body fat. There was no correlation between NECR and skeletal muscle mass. We could calculate the SNR and pNECR as follows

$$\mathrm{SNR}^2 = \mathrm{pNECR} \times (70\,\mathrm{kg}^{-0.84}/\mathrm{body\ weight}^{-0.84}) \times \mathrm{time}\,. \tag{3.4}$$

Finally, F_{TS} was as derived for individual patient's body weight and BMI

$$F_{TS} = 0.01\ \mathrm{body\ weight} + 0.2\,. \tag{3.5}$$

This equation meant that scan time for a 40 kg weighted person could be reduced by 40% compared to 70 kg person. In addition the scan time for 120 kg person needed to be lengthened by 80%.

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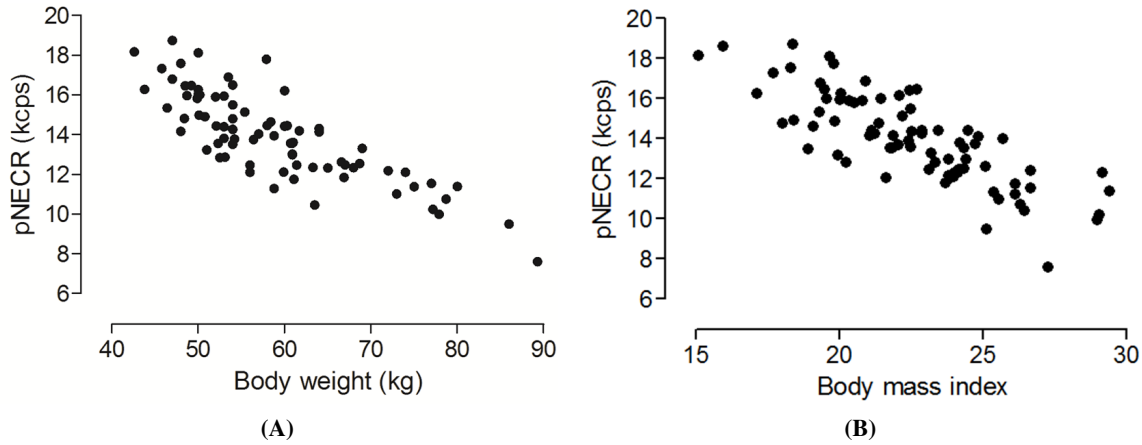

Figure 5. The plot of the pNECR and (A) body weight and (B) BMI.

4 Discussion

The aim of the present study was to derive the relationship between pNECR and body weight. In this present study we described a novel time scaling factor for maintaining a consistent PET image quality.

Recently, the European Association of Nuclear Medicine (EANM) provided the guidelines for tumor imaging using FDG PET. There was a prescription of patient preparation and precaution, pregnancy, breastfeeding, serum glucose level before FDG administration, diabetes, kidney failure, preparation and administration of FDG and contrast agent, PET acquisition protocol, CT protocol for FDG PET/CT study, image reconstruction, image analysis and SUV calculation, physiological FDG distribution and interpretation criteria, definition of volumes of interest, quality control of PET/CT system performance harmonization, radiation exposure to the patient, and recommendation for FDG dose and administered activity [14]. The guidelines for FDG dose were updated from EANM procedure guidelines for tumor imaging (version 1.0) [15]. According to EANM procedure guidelines for tumor imaging, version 2.0, the minimum acceptable administered activity of FDG (MBq) was 14 $(\mathrm{MBq}\cdot\mathrm{min}\cdot\mathrm{bed}^{-1}\cdot\mathrm{kg}^{-1})\times$ patient weight (kg)/emission acquisition duration per bed position $(\mathrm{min}\cdot\mathrm{bed}^{-1})$ for a PET bed overlap of less than 30%. In case of PET bed overlap greater than 30%, the minimum FDG administered activity was 7 $(\mathrm{MBq}\cdot\mathrm{min}\cdot\mathrm{bed}^{-1}\cdot\mathrm{kg}^{-1})\times$ patient weight (kg)/emission acquisition duration per bed position $(\mathrm{min}\cdot\mathrm{bed}^{-1})$. In EANM procedure guideline for tumor imaging: version 2.0, quadratic relationship between recommended FDG activity and patient's body mass was provided as a alternative. The activity was multiplied by the square of the patient weight/75. Prescribed FDG dose was categorized into two groups: body weight greater than 90 kg and body weight less than 90 kg or acquisition time per bed position (min) was 1 min for body weight greater than 60 kg, 2 min for body weight was 60 to 90 kg, and 3 min for body weight was grater than 90 kg. Using a dose regimen based on de Groot and colleagues' study, image quality was reported to be constant across the patients when quadratic relationship was used [16].

However, in our present study, we suggested the time scaling factor to maintain the consistency of PET image quality. The PET imaging acquisition time was very simple to calculate with our

suggested equation. In this study, we did not consider increasing the administered dose for FDG PET, because minimizing dose was advantageous in terms of radiation exposure to patients. There was a report stating that increase of dose did not improve the PET image quality [7], although the administered dose was low compared to calculated optimal dose based on NECR calculation according to NEMA NU2-2007. In this present study, we also derived time scaling factor for the maintaining the PET image quality using the relationship between pNECR and BMI.

According to the data, the relationship between abdominal circumference and BMI was as follows:

$$\text{Abdominal circumference } = 2.09\ (\text{BMI}) + 32.64\,. \tag{4.1}$$

The relationship between pNECR and BMI and the equation of time scaling factor was as follows:

$$\text{pNECR} = 36.96\ (\text{BMI})^{-0.04} \tag{4.2}$$

$$\text{F}_{\text{TS}} = 0.002\ \text{BMI} + 0.95\,. \tag{4.3}$$

However, time scaling factor using the relationship between pNECR and BMI was not appropriate. This was because that patient specific scatter fraction was derived based on the relationship between abdominal circumference and body weight. Height was not considered when scatter fraction was calculated. In contrast, height information was included in BMI. Therefore, time scaling factor using BMI information was not exactly modeled. Derivation of time scaling factor using BMI for maintaining the consistency of PET image quality was needed because BMI was a widely used index for the measurement of body fat based on height and weight. Difference between male and female was not also modeled in this study. Sex difference and BMI need to be included to derive the time scaling factor in further study.

Our study investigated the relationship between pNECR and multiple parameters including skeletal muscle mass, total protein amount, mineral mass, body fat percentage for individual subjects.

The time scaling factor developed in this work to maintain the consistency of PET image quality should be validated with actual PET scans. In our study, we did not apply our proposed model to actual individual PET studies due to the need of approval by the Korean Food and Drug Administration. After approval from the institutional review board and Korean FDA, our proposed method could be validated in further study.

5 Conclusion

In this present study, we developed the scan time requirement for maintaining a consistent PET image quality using Monte Carlo simulation based pNECR. The equation of the relative time demand derived in this study will be useful for maintaining consistent PET image quality in clinics.

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