The Impact of Patient’s Body Habitus on PET Image Quality in Digital and Analogic PET/CT

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Abstract

Background: New digital versus analogic PET has higher temporal resolution and more stable count rate, potentially limiting the degradation of PET image quality in larger patients. We wanted to describe the influence of patient's body habitus on $^{18}$F FDG PET image quality primary in digital PET/CT and analogic PET/CT.

Results:

We studied retrospectively the relation between patient's weight, BMI, fatty mass and PET image quality, described by the coefficient of variance in the liver ($\text{CV}_{\text{liv}}$) and visually.

177 unique patient exams on digital PET/CT (weight 35-127 kg; BMI 15-44 kg/m$^2$) were performed with 2 protocols (protocol 1: N=52: 3MBq (0,08mCi)/kg $^{18}$F FDG; 2minutes/bed position; 2iterations10subsets; 2mm diameter voxels and protocol 2: N=125: 4MBq (0,11mCi) /kg $^{18}$F FDG; 1min/bed position; 4iterations4subsets; 2mm voxels).

74 unique patient exams were analyzed on analogic PET/CT (weight 38-130 kg; BMI 14-52 kg/m$^2$; with one protocol: 4MBq (0,11mCi)/kg $^{18}$F FDG; 2min40sec/bedposition for BMI<25 and 3min40sec for BMI $\geq$ 25; 3iterations21subsets; 4mm voxels).

Uni-and multivariable linear regression analysis showed positive association of $\text{CV}_{\text{liv}}$ with weight, BMI, fatty mass (p£0.009) and male sex (p£0,03) for both camera's, with good fit in $\text{CV}_{\text{liv}}$ versus weight model on digital PET/CT ($R^2$ up to 0.62). 4MBq (0,11mCi) protocol on digital PET/CT versus analogic PET/CT obtained lower $\text{CV}_{\text{liv}}$ on digital PET/CT in patients <70kg, without a difference if 70<90kg and in Pearson correlation coefficients (p=0,26) despite substantially longer acquisition time for analogic PET/CT. For digital PET/CT $\text{CV}_{\text{liv}}$ increased similarly with weight for both protocols, up to 26% [95% Confidence Interval 2-56%] for $\geq$90 kg versus <70kg, but overall $\text{CV}_{\text{liv}}$ values were lower in 4MBq (0,11mCi) protocol 2.

Also visually PET image quality decreased with habitus on each camera (p£0.001) and was lower in females on digital PET/CT only (p=0,04).

Conclusions:

$^{18}$F FDG PET image quality decreases with weight and enlarging body habitus on digital and analogic PET/CT imposing further optimization and harmonization also in digital PET/CT. This is important for clinical routine, but also (multicentric) research and development of artificial intelligence software.

Background

Digital positron emission tomography/ computed tomography (dPET/CT) cameras with silicon photomultipliers (SiPM) detectors are a technological leap and can provide a diagnostic improvement [1]. They show high PET resolution and stable performance in count rate [2]. This is expected to decrease the deterioration of PET image quality (IQ) in function of patient's body habitus.
A comparison of the first digital time-of-flight (TF) PET/CT and analogic TF PET/CT in the same patients (consecutive imaging with randomized order) have shown a better or equivalent visual PET IQ on the digital camera [3,4].

PET IQ decreases with increasing body mass [5,6] and body mass index [7,8] on an analogic PET/CT (aPET/CT) camera. Signal to noise ratio in the liver (SNR\textsubscript{liv}) or inversely its coefficient of variance (CV\textsubscript{liv}), and noise equivalent count ratio (NECR) are used as (semi) quantitative indicators of PET IQ. Controversy exists about a linear [7], quadratical [5] or exponential [6,8] relation of these PET IQ parameters with body habitus on analogic PET/CT systems. The liver coefficient of variance (CV\textsubscript{liv}) can increase more than 26% between patients weighing less versus at least 70kg in a Japanese study [9]. The European association of nuclear medicine (EANM) imaging guidelines propose two possibilities for calculating the injected activity of [\textsuperscript{18}F]fluorodeoxyglucose ([\textsuperscript{18}F]FDG) in function of patient’s body mass in a linear and quadratical way [10].

variable scoring systems in studies [6,11-16].

To overcome degradation of analogic PET IQ in overweight and obese patients we can increase acquisition time and/or injected activity [8,13,15,16]. Also technical progress especially TF and optimization in reconstruction parameters [9,14,17] can contribute to obtain a more constant PET IQ. However little has been described about the necessity and modalities of these compensatory techniques in dPET/CT. Positive influence of acquisition time on PET IQ in dPET/CT has been reported in 58 oncologic patients [18].

Our primary goal was characterizing on digital PET/CT the relation between patient’s body mass index (BMI), weight, fatty mass (FM) and [\textsuperscript{18}F]FDG PET image quality, as an important first step towards optimizing and harmonizing imaging protocols in digital PET/CT.

Materials And Methods

Patient population: Patients referred to our oncological institution for [\textsuperscript{18}F]FDG PET/CT between February 2018 and March 2020 for dPET/CT and January 2014 and February 2019 for aPET/CT were retrospectively included, with only one study per patient. We obtained approval of institutional review board (IRB) and informed consent (non-opposition) of all patients. This observational study was conform MR 004, a national French institution (INDS) defining health research conduct guidelines. Study exclusion criteria were diabetes, glycaemia before [\textsuperscript{18}F]FDG injection > 150mg/dl; missing or inconsistent patient’s data; major (respiratory) image motion artifacts; acquisition with arms along the body; paravenous injection in the image or mentioned in the report; at least one hepatic metastasis; a diffuse or extensive visualized pulmonary or hepatic pathology like evident hepatic steatosis on CT (Hounsfield units liver <40); advanced multimetastatic, high uptake disease; recent chemotherapy and growth factors (<2weeks) with important activity shift towards spleen and/or bone and important diffuse bowel, brown fat or muscle uptake. Image protocol

Both PET centres are accredited by EANM research limited (EARL) [19] and EANM imaging guidelines were respected [10].

Patients fasted for at least 6h before [\textsuperscript{18}F]FDG injection. Patients’ weight was checked on a calibrated scale [20].
For dPET/CT: **protocol 1** consisted of 3MBq (0,08mCi)/kg $^{[18]}$F-FDG (8%) – 2min/bed position- 3D ordered subset expectation maximization (OSEM) point spread function (PSF) reconstruction with 2 iterations 10 subsets (2i10s) and 2mm voxel size diameter.

In **Protocol 2**, implemented in a period of increased patient number scanning, we adopted 4MBq (0,11mCi)/kg $^{[18]}$F-FDG (8%) -1min/bed position-3D OSEM PSF reconstruction; 4i4s, 2mm voxel size diameter.

For aPET/CT: 4.0 MBq/kg $^{[18]}$F-FDG (8%) and a variable acquisition time per bed position was used: 2min40s for patients with BMI < 25 kg/m$^2$ and 3min40s for patients with BMI ≥ 25 kg/m$^2$. A 3D-OSEM PSF reconstruction with 3i21s and 4mm voxel size was performed, all with scatter and attenuation correction.

**Image Quality Analysis 1. Semi-Quantitative Analysis** 1 spherical volume of interest (VOI) in the liver with a 2,5 to 3cm radius (Nvoxels >>100) was drawn on PSF PET reconstruction data, avoiding upper parts with respiratory artefacts, main large hepatic vessels and tissue boundaries, using Slicer: [https://www.slicer.org/](https://www.slicer.org/) [21]. CV$^{\text{liv}}$ was measured in each liver VOI with CV with the * standardized uptake value (SUV) based on the body weight (SUV$^{\text{bw}}$ or simplified SUV) Measures were automatically extracted with in house software based on ITK [22]. Patients’ weight (kg) and length (m) were extracted from PET DICOM data and verified in the PET report -BMI (kg/m$^2$) = weight/ (length)$^2$[23] and fatty mass (FM) = weight (kg) – lean body mass (LBM, kg). LBM was estimated with the Janma formula, more adapted for very obese women [24].

**Visual analysis** A 5-point global image quality score (Likert score) (visual IQ$^{\text{G}}$) was given individually by 2 nuclear medicine physicians (with >10 years experience), blinded for clinical information, for 3MBq (0,08mCi) protocol 1 on dPET/CT and aPET/CT. Scoring was defined as: 5=excellent, 4=good, 3=fair, 2=poor, 1=bad. This global score was based on liver homogeneity, global image noise, image contrast and correct visualization of regions with very low activity (mostly evaluated at intervertebral spaces), as well as the absence of artefacts around high activity regions (bladder). A 10-point score (0-5 with 0,5 interval) of hepatic homogeneity (IQ$^{\text{H}}$) only was also collected separately on dPET/CT 3MBq (0,08mCi) protocol 1, validated by repeated pairwise comparison in order to classify them [25].

**Statistical analysis** STATA version 15 was used for analyses. The normality distribution of BMI, weight and fatty mass were evaluated using a Shapiro–Wilks test. We performed linear regression analysis to investigate the association between weight, BMI, fatty mass and CV$^{\text{liv}}$ on each camera. We ran camera dependent stratified multivariable analyses, and tested whether adjustment on other variables changed association. Linear goodness of fit was compared with exponential and quadratic transformations. Cohen's kappa was used for evaluating the visual IQ agreement and Spearman's rho for the correlation between the clinicians' visual IQ and weight, BMI, CV$^{\text{liv}}$. All tests were two sided, with p<0.05 considered to be statistically significant.

**Results**

**Patient's population** 177 unique patient exams on dPET/CT: 52 with 3MBq (0,08mCi) protocol 1 and 125 with 4MBq (0,11mCi) protocol 2, and 74 patients on aPET/CT were analyzed.

$^{[18]}$F-FDG PET/CT indication was in 80 to 82 percent of patients oncological (initial or follow-up exam in proven malignancy), versus diagnostic (benign versus malignant pathology) or miscellaneous (inflammatory or infectious pathology).

**Table 1:** Patient and PET/CT characteristics
|                  | dPET/CT                  | aPET/CT                  |
|-----------------|--------------------------|--------------------------|
| **Protocole 1** | N=52                     | N=74                     |
| **Protocole 2** | N=125                    |                          |
| **Sex**         | 58%                      | 60%                      | 47%                      |
| **Age (Y) mean±SD** | 62.3±14.7                | 60.9±13.6                | 62.8±13.0                |
| [range]         | [23-89]                  | [24-89]                  | [22-81]                  |
| **Weight (kg) mean±SD** | 78±19                    | 75±16                    | 80±23                    |
| [range]         | [41-127]                 | [35-110]                 | [38-130]                 |
| **Height (m) mean±SD** | 1.67±0.10                | 1.66±0.10                | 1.67±0.09                |
| [range]         | [1.46-1.83]              | [1.51-1.85]              | [1.48-1.84]              |
| **BMI (kg/m2) mean±SD** | 28±8                    | 27±8                    | 28±8                    |
| [range]         | [15-44]                 | [15-42]                  | [14-52]                  |
| **Fat (kg) mean±SD** | 27±12                    | 25±13                    | 27±14                    |
| [range]         | [6-63]                  | [5-60]                   | [3-74]                   |
| **Glycaemia (g/l) mean±SD** | 1.02±0.18[0.76-1.5]     | 1.01±0.13[0.70-1.38]    | 0.98±0.11[0.72-1.25]     |
| [range]         |                          |                          |                          |
| **Scan Delay (min)** | 58.5±2.7                | 58.3±3.0                 | 58.0±3.0                 |
| mean±SD         |                         |                          | idem                    |
| [range]         | [55-65]                 |                          |                          |
| **Injected Activity/kg** | 3.0±0.1 MBq/kg           | 4.0±0.2 MBq/kg           |                          |
| [¹⁸F]FDG mean±SD | 0.08±0.003 mCi (8%)      | 0.11±0.015 mCi (8%)      |                          |
| [range in %/patient] |                          |                          |                          |
| **Bedposition scan duration** | 120 sec                 | 60 sec                  | 160 sec BMI<25kg/m²      |
|                  |                          |                          | 220 sec BMI≥25kg/m²      |
| **Reconstruction protocol** | 3D OSEM + PSF 2i10s     | 3D OSEM + PSF; 4i4s     | 3D OSEM + PSF 3i21s     |
|                  | 2mm voxel size           | 2mm voxel size          | 4mm voxel size         |

without significant differences between groups in age, sex, weight, height, BMI, glycaemia, scan delay.

*Image Quality Analysis*
1. Semi-Quantitative Analysis

On dPET/CT (with both imaging protocols) and aPET/CT, CV\text{liv} was associated with weight, BMI and fatty mass in univariable and multivariable linear regression analyses ($p<0.0001$ for dPET/CT and $p<0.009$ for aPET/CT). There was also a significant, more moderate association between sex and CV\text{liv} with higher CV\text{liv} in men on both camera's, only for dPET/CT 4MBq (0,11mCi) protocol 2 in multivariable weight models ($p=0.03$), and except for dPET/CT 3MBq (0,08mCi) protocol in multivariable BMI models ($p<0.01$).

Age, pathological exam, initial exam were not associated with CV\text{liv}.

The $R^2$-t association of CV\text{liv} was best described by a linear model and reached a good and same univariable and multivariable fit in weight model on dPET/CT 3MBq (0,08mCi) protocol 1; $R^2=0.62$ (versus multivariable $R^2=0.40$ for 4MBq (0,11mCi) protocol 2 and $R^2=0.26$ on aPET/CT). For CV\text{liv} versus fatty mass no differences in linear fitting were found. However not significantly different ($p<0.54$), in both protocols on dPET/CT slightly less well linear fitting ($\approx-10\%$) was obtained between CV\text{liv} and BMI (versus weight) for dPET/CT (for dPET/CT protocol 1:$R^2=0.54$ versus 0.36 in protocol 2 and 0,26 on aPET/CT).

**Figure1.** Graph formula (univariable linear regression) was the following: $CV_{liv} = 6,2.10^{-4} (\pm 7,2.10^{-5}) \times \text{weight} + 7,6.10^{-2} (\pm 5,5.10^{-3})$. In this group no additional sex effect was found.

Better results with lower mean CV\text{liv} values were obtained with 4MBq (0,11mCi) protocol 2 versus 3MBq (0,08mCi) protocol 1 on dPET/CT. However slopes, curve coefficients of weight in the linear formula predicting CV\text{liv} were not significantly different ($p=0,72$).

On dPET/CT compared to weight category $< 70$kg as a reference, patient category $70 <90$kg had on average a significantly higher CV\text{liv} (+7%, range [-9% to 24%]) for 3MBq (0,08mCi) protocol 1 and +9% range [-13% to 36%]) for 4MBq (0,11mCi) protocol 2; $p<0.02$). More pronounced relative CV\text{liv} increase was observed for patients $>90$ kg (+22% [-3%-50%] for 3MBq (0,08mCi) protocol 1 + 26% [2%-56%] for 4MBq (0,11mCi) protocol 2).

**Table 2: Mean CV\text{liv} in weight categories**
With significant lower CV_{liv} values on dPET/CT with 4MBq protocol 2 versus 3MBq protocol 1 in each weight category (p=0.01 <70kg and p=0.049 in 70-89kg) except for 90kg (p=0.2).

Between 4MBq (0.11mCi) protocol 2 on dPET/CT and aPET/CT lower CV_{liv} in patients <70kg on dPET/CT and no significantly different CV_{liv} in intermediate weight category and Pearson's correlation coefficients (R) were found (p≥0.26), despite longer mean scanning time and per bed position for aPET/CT. However curve slope of CV_{liv} versus weight was significantly steeper for dPET/CT (p=0.00005), although flattened and not comparable on aPET/CT in particular by its BMI adaptive protocol.

2. Visual IQ analysis

Table 3: Visual IQ per reader, camera, and weight category

|               | dPET/CT          | aPET/CT          | ALL             |
|---------------|------------------|------------------|-----------------|
|               | protocol 1       | N=74             | N=126           |
| N=52          |                  |                  |                 |
| Reader 1      | 3,39/5 ±0,63     | 3,53/5 ±0,57     | 3,48/5 ±0,60    |
| (mean score  |                  |                  |                 |
| ±SD)         |                  |                  |                 |
| Reader 2      | 3,61/5 ±0,67     | 3,81/5 ±0,51     | 3,73/5 ±0,58    |
| (mean score  |                  |                  |                 |
| ±SD)         |                  |                  |                 |
| Total mean    | 3,50/5 ±0,66     | 3,67/5 ±0,56     | 3,60/5 ±0,60    |
| score ±SD    | 3,90 ± 0,53 (N=21)3,30 ± 0,60 | 3,95 ± 0,44 (N=29)3,69 ± 0,52 |                  |
| § <70kg       |                  |                  |                 |
| § 70 <90kg    |                  |                  |                 |
| § ≥90 kg      |                  |                  |                 |
Lower scores if <70kg versus <70kg for dPET/CT (p<0.003) and between each higher weight category for aPET/CT (p<0.008). Higher overall scores and in categories <70 kg on aPET/CT versus dPET/CT (p<0.03).

Significant higher scores by reader 2 (all patients summed; p=0.0009).

Interreader Cohen's kappa was only moderate between both readers, identical on both camera's (κ=0.4).

For both readers there was a significant and similar negative relation of visual image quality score and BMI and weight (p<0.0001) on both camera's.

Table 4: Relation between visual IQ, weight and BMI

| Visual IQ | dPET/CT protocol 1 | aPET/CT |
|-----------|---------------------|---------|
|           | Weight Reader 1 Reader 2 | Weight Reader 1 Reader 2 | BMI Reader 1 Reader 2 |
| Spearman rho | -0.60 -0.63 | -0.66 -0.68 | -0.47 -0.45 | -0.50 -0.49 |

Figure 2. Graph 2

Lower global IQ was found in women on dPET/CT only (3.41/5 versus 3.60/5; p=0.04), without sex difference in hepatic homogeneity scores.

For both readers there was a significant and similar negative relation of global visual IQ and CV<sub>liv</sub> for both camera's (spearman rho κ = -0.4; p<0.05), higher when scoring only visual hepatic homogeneity in a pair-wise comparison (κ = -0.65; p=0.001).

Visual analysis was not performed for 4MBq (0.11mCi)/kg protocol 2 on dPET/CT as semi-quantitative data were comparable in both protocols.

3. Case examples (figure 3)

Discussion

In dPET/CT both imaging protocols with different acquisition time, injected activity and reconstruction parameters showed the same semi-quantitative relationship, extending its applicability.

To best of our knowledge this is the first study of the impact of patient's habitus on PET image quality in digital PET/CT camera's, which is a very important step towards optimizing imaging protocols in these new camera's.

Digital PET/CT systems present an increased temporal resolution and stability in count rate [2] versus analogic PET/CT systems. However this doesn't compensate for the increase in noise and decrease of image quality with increasing patient's weight and habitus. In obese and overweight patients higher random counts, scatter activity besides attenuation and possibly pathologic hepatic heterogeneity may play a role in generating extra image noise.
A linear increase of the coefficient of variance, noise in the liver, was observed, with larger habitus and in particular weight for dPET/CT. However not significantly different, slightly higher fitting of CV\textsubscript{liv} in function of weight versus BMI was obtained. Fatty mass was equally fitted as weight but is not readily useable in clinical routine.

The linearity of the relation between patient's weight, BMI, fatty mass and CV\textsubscript{liv} is controversial in literature. Different teams have described linear, exponential or quadratic estimated fittings on analogic PET/CT camera's [5-8].

In multivariable analyses we also observed a moderate extra effect of sex with higher CV\textsubscript{liv} in men in some groups and regression models, without matching criteria for confounder.

Possibly increased incidence of metabolic syndrome in men with higher abdominal fat and/or attenuation and controversially higher heterogeneity in hepatic uptake in steatohepatitis [26], more frequent in men [27] could explain this difference. Obvious hepatic steatosis on CT (of PET/CT) was excluded, however no splenohepatic density comparison was used. We didn't measure abdominal waist or fat content.

On dPET/CT better IQ with lower mean CV\textsubscript{liv} values were obtained with 4MBq (0,11mCi) protocol versus 3MBq (0,08mCi) protocol, despite of a lower time activity product (4 versus 6). The association with weight was similar however. The PSF reconstruction was also altered from 2i10subsets for the 3MBq (0,08mCi) protocol to 4i4subsets for the 4MBq (0,11mCi) protocol, based on phantom studies and verified in clinical test patients.

There was a better IQ with lower CV\textsubscript{liv}, in dPET/CT versus aPET/CT in 4MBq (0,11mCi)/kg protocols for patients<70kg and no significant difference of CV\textsubscript{liv} in intermediate weight category nor between correlation coefficients (Pearson, in weight and BMI models), despite of a BMI adaptive protocol, and with substantially longer mean scanning time and per step for all patients on aPET/CT. On dPET/CT also a smaller 2mm voxel size diameter was used versus 4mm on aPET/CT. Smaller voxel size increases image noise, by dividing detected number of photons, but improves small lesion detectability [28].

Similar negative correlation was found between visual [\textsuperscript{18}F]FDG PET image quality of both readers and patient's weight and BMI, on both camera's. The influence of sex was however opposite on dPET/CT for global visual IQ (lesser quality in women) and not found in visual hepatic homogeneity scores.

CV\textsubscript{liv} was correlated with global visual IQ for both readers and even better with visual hepatic heterogeneity only. Global visual IQ was besides liver homogeneity and image noise, image contrast and adequate visualization of low activity zones, also based on blinding artefacts around high activity zones (especially bladder) which were quite frequently seen on aPET/CT and not on dPET/CT. A more stable PET counting rate (with less dead time effects) in and around high activity areas is certainly an advantage of dPET/CT [2]. Unweighted Cohen's kappa for visual IQ between both readers was only moderate but identical on both camera's. Moreover one reader scored consistently a bit higher.

Study limitations are the retrospective and different study populations and protocols. Normal and slightly overweight patients were overrepresented, especially in the 4MBq (0,11mCi) protocol in dPET/CT.

Study evaluation parameters were based mainly on image noise and contrast in normal organs but don't take into account (small) lesion detectability.
Improvement of PET IQ in larger and higher weight patients and IQ harmonization are very important for exam accuracy, intrapatient follow-up (for instance in case of weight fluctuations) as well as harmonization interpatient and intermachine in clinical routine, research and development of artificial intelligence software.

The next step towards improvement of $[^{18}\text{F}]$FDG PET IQ in dPET/CT will be to evaluate an adjusted PET protocol.

Our aim will be to keep constant PET IQ with a CV$_{\text{liv}}$ of 0.122 ± 0.008 corresponding to a and with a visual IQ score of at least 4 as second criterion, which has to be fulfilled in at least 84% of our patients.

For this we can increase injected activity and/or acquisition time per bed position (in function of weight) and/or use technical solutions.

We will study two methods based first on imaging denoising software and secondly an adaptive acquisition time/bed position in function of weight categories. PSF reconstruction 4i4s is withheld. We chose not to include sex as a parameter given conflicting semi-quantitative and visual data in this regard.

Imaging denoising software based on artificial intelligence, like subtle PET$^\text{TM}$ by Subtle Medical is a very promising, FDA approved tool [29,30] which can even allow decrease in acquisition time and/or injected activity to keep a good and ideally constant IQ. The first step would be to reevaluate all study patients retrospectively with this software. Second ideally a prospective study of both strategies will be done.

In the second strategy we prefer not to increase injected activity above 3MBq (0.08mCi)/kg mostly for radioprotection and practical reasons.

For the adaptive scan duration the conservative mean acquisition time per bed position can be calculated via the 3MBq (0.08mCi) protocol formula obtained by the univariable fitted plot of CV$_{\text{liv}}$ versus weight (with the ancient reconstruction protocol) and the estimated effect of scan duration. We have however some uncertainty about the level of influence of the reconstruction versus the injected activity on IQ, rendering the formula rather conservative. The effect of acquisition time/bed position is based on phantom data verified in clinical test patients. Patients are categorized in (7) weight categories, using calculated acquisition time/bed position for the highest weight in each category. For patients with a low weight a verification of possible decrease in acquisition time is performed in test patients.

With either strategy we hope to reduce significantly the impact of patient’s body habitus on $[^{18}\text{F}]$FDG PET image quality and improve and harmonize further PET/CT studies.

**Conclusion**

$[^{18}\text{F}]$FDG PET image quality, evaluated by CV$_{\text{liv}}$ and visually, decreases with increasing patient’s body habitus and especially weight on digital and analogic PET/CT. This study is a first step towards optimizing and harmonizing $[^{18}\text{F}]$FDG PET also in new digital PET/CT, important for clinical routine, (multicentric) research and development of artificial intelligence software.

**Abbreviations**
PET/CT: positron emission tomography / computed tomography

SiPM: silicon photomultipliers

$[^{18}F]FDG$ : $[^{18}F]$fluorodeoxyglucose

IQ: image quality

TF: time-of-flight

$\text{SNR}_{\text{liv}}$: signal to noise ratio in the liver

$\text{CV}_{\text{liv}}$: coefficient of variance in the liver

NECR: noise equivalent count ratio

EANM: The European association of nuclear medicine

BMI: body mass index

FM: fatty mass

MBq (mCi): MegaBecquerel (millicurie)

OSEM: ordered subset expectation maximization

PSF: point spread function

VOI: volume of interest

SUV: standardized uptake value

SD: standard deviation

LBM: lean body mass

$\text{IQ}_G$: global visual PET image quality

$\text{IQ}_H$: hepatic visual PET image quality

CMR: complete metabolic remission or response

**Declarations**

*Ethics approval and consent to participate and for publication*

This observational study was conform MR 004, in collaboration with the research unit of the centre François Baclesse, Caen, France. An informed absence of opposition (non-opposition) of use of all patient data in the view of a publication was obtained for each study patient.
Availability of data and materials

Data resume generated or analysed during this study are included in this published article [and its supplementary information files]

Other datasets used and/or analysed during this study are available from the corresponding author on reasonable request.

Competing interests:

The authors declare that they have no competing interests

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Author’s contributions

KW collected patient data, designed the methodology and performed visual and semi-quantitative analysis of all patients with analysis of results and wrote the manuscript draft.

EQ was the second reader in the visual analysis and participated in discussions about study design.

IL substantially contributed in the whole study design, performed the gross majority of statistical analysis, made manuscript graphs, and substantially revised the manuscript. CL, RC, JFS, GF, SB participated in discussions about study design. CJ had the idea and initiated the study, created and helped in using the software allowing data analysis and revised the manuscript. All authors read and approved the final manuscript

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References

1. Zhang J, Maniawski P, Knopp MV. Performance evaluation of the next generation solid-state digital photon counting PET/CT system. EJNMMI Res. 2018;8:97.
2. Miller M, Zhang J, Binzel K, Griesmer J, Laurence T, Narayanan M, et al. Characterization of the Vereos Digital Photon Counting PET System. J Nucl Med. 2015;56:434–434.
3. López-Mora DA, Flotats A, Fuentes-Ocampo F, Camacho V, Fernández A, Ruiz A, et al. Comparison of image quality and lesion detection between digital and analog PET/CT. Eur J Nucl Med Mol Imaging. 2019;46:1383–90.
4. Nguyen NC, Vercher-Conejero JL, Sattar A, Miller MA, Maniawski PJ, Jordan DW, et al. Image Quality and Diagnostic Performance of a Digital PET Prototype in Patients with Oncologic Diseases: Initial Experience and Comparison with Analog PET. J Nucl Med. 2015;56:1378–85.
5. de Groot EH, Post N, Boellaard R, Wagenaar NR, Willemsen AT, van Dalen JA. Optimized dose regimen for whole-body FDG-PET imaging. EJNMMI Res. 2013;3:63.
6. McDermott GM, Chowdhury FU, Scarsbrook AF. Evaluation of noise equivalent count parameters as indicators of adult whole-body FDG-PET image quality. Ann Nucl Med. 2013;27:855–61.

7. Queiroz MA, Wollenweber SD, von Schulthess G, Delso G, Veit-Haibach P. Clinical image quality perception and its relation to NECR measurements in PET. EJNMMI Phys. 2014;1:103.

8. Chang T, Chang G, Kohlmyer S, Clark JW, Rohren E, Mawlawi OR. Effects of injected dose, BMI and scanner type on NECR and image noise in PET imaging. Phys Med Biol. 2011;56:5275–85.

9. Taniguchi T, Akamatsu G, Kasahara Y, Mitsumoto K, Baba S, Tsutsui Y, et al. Improvement in PET/CT image quality in overweight patients with PSF and TOF. Ann Nucl Med. 2015;29:71–7.

10. Boellaard R, Delgado-Bolton R, Oyen WJG, Giammarile F, Tatsch K, Eschner W, et al. FDG PET/CT: EANM procedure guidelines for tumour imaging: version 2.0. Eur J Nucl Med Mol Imaging. 2015;42:328–54.

11. Masuda Y, Kondo C, Matsuo Y, Uetani M, Kusakabe K. Comparison of imaging protocols for 18F-FDG PET/CT in overweight patients: optimizing scan duration versus administered dose. J Nucl Med. 2009;50:844–8.

12. Visvikis D, Griffiths D, Costa DC, Bomanji J, Ell PJ. Clinical evaluation of 2D versus 3D whole-body PET image quality using a dedicated BGO PET scanner. Eur J Nucl Med Mol Imaging. 2005;32:1050–6.

13. Tatsumi M, Clark PA, Nakamoto Y, Wahl RL. Impact of body habitus on quantitative and qualitative image quality in whole-body FDG-PET. Eur J Nucl Med Mol Imaging. 2003;30:40–5.

14. Akamatsu G, Ishikawa K, Mitsumoto K, Taniguchi T, Ohya N, Baba S, et al. Improvement in PET/CT image quality with a combination of point-spread function and time-of-flight in relation to reconstruction parameters. J Nucl Med. 2012;53:1716–22.

15. Everaert H, Vanhove C, Lahoutte T, Muylle K, Caveliers V, Bossuyt A, et al. Optimal dose of 18F-FDG required for whole-body PET using an LSO PET camera. Eur J Nucl Med Mol Imaging. 2003;30:1615–9.

16. Halpern BS, Dahlbom M, Auerbach MA, Schiepers C, Fueger BJ, Weber WA, et al. Optimizing imaging protocols for overweight and obese patients: a lutetium orthosilicate PET/CT study. J Nucl Med. 2005;46:603–7.

17. Akamatsu G, Mitsumoto K, Ishikawa K, Taniguchi T, Ohya N, Baba S, et al. Benefits of point-spread function and time of flight for PET/CT image quality in relation to the body mass index and injected dose. Clin Nucl Med. 2013;38:407–12.

18. Sonni I, Baratto L, Park S, Hatami N, Srinivas S, Davidzon G, et al. Initial experience with a SiPM-based PET/CT scanner: influence of acquisition time on image quality. EJNMMI Phys. 2018;5:9.

19. Aide N, Lasnon C, Veit-Haibach P, Sera T, Sattler B, Boellaard R. EANM/EARL harmonization strategies in PET quantification: from daily practice to multicentre oncological studies. Eur J Nucl Med Mol Imaging. 2017;44:17–31.

20. Lasnon C, Houdu B, Kammerer E, Salomon T, Devreese J, Lebasnier A, et al. Patient’s weight: a neglected cause of variability in SUV measurements? A survey from an EARL accredited PET centre in 513 patients. Eur J Nucl Med Mol Imaging. 2016;43:197–9.

21. Kikinis R, Pieper SD, Vosburgh KG. 3D Slicer: a platform for subject-specific image analysis, visualization, and clinical support. Intraoperative imaging and image-guided therapy. Springer; 2014. p. 277–289.

22. Schroeder W, Ng L, Cates J. The ITK software guide. 2003;

23. Health NI of. Clinical guidelines for the identification, evaluation, and treatment of overweight and obesity in adults-the evidence report. Obes Res. 1998;6:51S-209S.
24. Tahari AK, Chien D, Azadi JR, Wahl RL. Optimum lean body formulation for correction of standardized uptake value in PET imaging. J Nucl Med. 2014;55:1481–4.

25. Mantiuk RK, Tomaszewska A, Mantiuk R. Comparison of four subjective methods for image quality assessment. Computer graphics forum. Wiley Online Library; 2012. p. 2478–2491.

26. Keramida G, Potts J, Bush, Verma S, Dizdarevic S, Peters AM. Accumulation of 18F-FDG in the liver in hepatic steatosis. Am J Roentgenol. 2014;203:643-648.

27. Ballestri S, Nascimbeni F, Baldelli E, Marrazzo A, Romagnoli D, Lonardo A. NAFLD as a sexual dimorphic disease: role of gender and reproductive status in the development and progression of nonalcoholic fatty liver disease and inherent cardiovascular risk. Adv Ther. 2017; 34: 1291-1326.

28. Koopman D, Van Dalen JA, Lagerweij MC, Arkies H, de Boer J, Oostdijk AHJ, et al. Improving the detection of small lesions using a state-of-the-art time-of-flight PET/CT system and small-voxel reconstructions. J Nucl Med Technol. 2015;43: 21-27.

29. Tanenbaum L. Artificial Intelligence and Medical Imaging: Image Acquisition and Reconstruction. Appl Radiol. 2020;49:34-35.

30. https://builders.intel.com/ai/solutioncatalog/subtlepet-542

**Figures**
Figure 1

Graph 1: Liver CV in function of weight on dPET/CT 3MBq (0.08mCi) protocol
Figure 2

Graph 2: Distribution of visual image quality scores in 3 weight categories on dPET/CT 3MBq (0.08mCi) protocol
Only few patients on dPET/CT had a score 2 (N=3; 5%) or 5 (N=4; 7%) by at least one reader.
Case examples Coronal [18F]FDG PET patient images A-C: dPET/CT 3MBq (0.08mCi) protocol 1 A. F 39Y 60kg 1,66m BMI=21,8 Estimated fatty mass=21kg Breast cancer follow-up: Complete metabolic remission (CMR) CVliv= 0,121 IQG = 4 and 5/5 (for each reader respectively); IQH 4/5 B. F 62Y 74kg 1,48m BMI=33,8 Estimated fatty mass=34kg Mediastinal lymph nodes without increased uptake CVliv= 0,138 IQG = 3 and 3/5 IQH 3/5 C. F 52Y 120kg 1,66m BMI=43,5 Estimated fatty mass=63kg Cervix and ovarian cancer in CMR CVliv= 0,174 IQG = 2 and 2/5 IQH 2/5 D-F: aPET/CT D. F 61Y 58kg 1,63m BMI=21,8. FM=20kg Colon cancer in CMR CVliv= 0,107 IQG = 4 and 4/5 IQH 4/5 E. F 50Y 76kg 1,56m BMI= 31,2. FM=33kg Vulva cancer in CMR CVliv= 0,112 IQG = 4 and 4/5 IQH 4/5 F. F 71Y 110kg 1,66m BMI= 39,9. FM=55kg Cervical cancer initial staging CVliv= 0,141 IQG = 3 and 3/5 IQH 3/5

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