A PET/CT Phantom for evaluating the PET image quality of micro-lesion and CT performance parameters

Shujie Lu¹⁺, Peng Zhang¹⁺, Chengwei Li¹, Jie Sun¹, Wenli Liu¹, Pu Zhang¹*  

Abstract

Background: Recent years, PET/CT equipment has played an increasingly important role in the medical field, and its quality control and evaluation requirements have become more stringent. Correspondingly, the performance testing phantom used for PET/CT quality control needs to be upgraded and optimized to meet the requirement of equipment imaging quality testing. The commonly used NEMA IEC Body performance testing phantom has the defects that it cannot detect micro-lesion and cannot measure CT performance parameters. This article proposes a NIM PET/CT phantom capable of simultaneously testing the performance of PET and CT equipment, and evaluates its imaging quality.

Methods: Compared with the NEMA IEC Body phantom, the PET performance testing module in the phantom has new balls with inner diameters of 4mm and 7mm. Combined with the CT performance testing module, it can be used for both PET and CT performance testing. The 28mm and 37mm balls are filled with pure water as a cold stove, and the remaining balls are filled with F-FDG solution as a hot stove. The activity concentration ratio of the hot ball to the background is 4:1. This study compares the imaging results of the NIM PET/CT phantom and the NEMA IEC Body phantom to verify its effectiveness; compares the imaging results of 3 different brands of PET/CT on the NIM phantom to verify that it is on different equipment The generalization ability of the system; apply PSF and TOF technology to the
reconstruction algorithm and compare the improvement of the image quality; finally, the accuracy of the CT low-contrast module and the uniformity of the background are verified.

**Results:** The imaging quality of the NIM PET/CT phantom and the NEMA IEC Body phantom is relatively consistent. The NIM phantom under different types of PET/CT scans can detect 7mm balls without affecting the imaging quality of other areas, which is better. The device can detect 4mm small balls, which can clearly classify the ability of different devices to present images of small lesions; the integration of PSF technology into the reconstruction algorithm significantly improves the image resolution and hot bulb contrast, but the edges of the lesions are still blurred. TOF technology improves the detection limit of the equipment and improves the overall quality of the image. PSF&TOF technology combines the advantages of the two, significantly reducing image noise and strengthening image details, so that the image quality has been comprehensively improved; the measurement in the CT module The result is consistent with the true value, and the relative error is within ±5%. The CT value transition between the background and pure water area is smooth, and the background uniformity is good.

**Conclusion:** NIM PET/CT Phantom and NEMA IEC Body phantom are comparability, and the former includes all the functions of the latter. In addition, the phantom can meet the testing requirement of different grades of PET/CT.

**Keywords:** PET/CT phantom, Performance test, Image quality, Limit detect ability,
Background

Positron emission Tomography (PET) utilizes gamma rays generated by the decay of radioactive drugs in body to reconstruct images\textsuperscript{[1]}, which can reflect the functional metabolism of lesions with high sensitivity but low resolution\textsuperscript{[2-4]}. Computed tomography (CT) utilizes different abilities of different human tissues for absorbing X rays and then analyzes the intensity of the X rays transmitted through the human body to reconstruct the tomography image\textsuperscript{[1]}, which can reflect the anatomical structure of lesions and have higher resolution than the functional image. With the development of medical imageology and the considerable progress of imaging technology, medical image fusion eliminates the physical limitation of imaging technology and improves the imaging quality\textsuperscript{[2]}, so as to obtain a more comprehensive and reliable lesion has become a major trend of medical imaging. PET/CT system combines the dual advantages of functional images and anatomical images, could improve staging by identifying local regional disease and occult metastatic disease\textsuperscript{[5]} with high sensitivity, high specificity and high accuracy.

PET/CT has evolved to be an essential imaging modality in oncology, cardiology, and neuroscience nowadays, corresponding quality control demand tend to unceasingly enhance. Due to the complex interplay of different aspects of system performance, it is desirable to be able to compare the image quality of different imaging system for a standardized imaging situation that simulates a clinical imaging
condition\textsuperscript{[6-8]}. In 1994, the National Electrical Manufacturers Association (NEMA) published the NEMA NU2-1994 standard for performance measurement of PET. Since then, the NEMA NU2 standard and the IEC61675-1 standard issued by the International Electrotechnical Commission (IEC) have undergone several revisions and cross-references. The NEMA IEC Body phantom is recommended by NEMA NU2 standard and is designed for PET image quality measurement, which is characterized by image contrast and background variability of hot and cold lesions, and accuracy of scattering correction and attenuation correction measured by lung residual error. The PET component of PET/CT equipment is evaluated using the method described in the NEMA standard and the CT component mainly focuses on low contrast resolution, the ability to resolve a limit size of given contrast and specific shape in uniform background is evaluated with other applicable standards\textsuperscript{[8,9]}.

Although NEMA IEC Body phantom is widely used, it still has some inevitable defects: 1. The minimum inner diameter of spheres used to measure image quality parameters in phantom is 10mm, so the phantom can not detect the limit of PET/CT\textsuperscript{[10]}, which is difficult to meet the requirements of detecting the small lesions in PET/CT system. 2.NEMA IEC Body phantom can only be used to performance measurement of PET, when it uses with Catphan phantom which is used to determine the low-contrast resolution of CT, the PET image will be contaminated by scattering. As a result, the performance evaluation of PET and CT must be carried out step by step, which increases the measurement time and introduces errors such as locating errors at the same time. 3.The lung insert of the phantom is easy to float on the surface of the solution and difficult to install, thus increasing the solution preparation time and the dose of ionizing radiation to the radiologist. Therefore, it is necessary to design a fully functional PET/CT phantom that can simultaneously complete all tests and is easy to assemble.

**Methods**
NEMA IEC Body phantom

NEMA IEC Body phantom\textsuperscript{[8]} is the anthropomorphic phantom recommended by both NEMA and IEC, paired with the NEMA NU2 standard, is a very common PET image performance measurement model at present.

The phantom is built of acrylic glass material, 6 hollow glass spheres and lung insert are inserted into it as hot and cold lesions\textsuperscript{[8,11,12]}. The two largest spheres (28 mm and 37 mm) shall be filled with non-radioactive water for cold lesion imaging and the rest with $^{18}$F for hot lesion imaging. And the cylindrical lung insert is filled with a low atomic number material with an average density of 0.30 ± 0.10 g/cc to simulate the attenuation of lung(Fig. 1).

![Fig. 1 NEMA IEC Body phantom](image)

NIM PET/CT phantom

The phantom in this study is composed of PET image quality phantom and CT image quality phantom through bolt combination, which can simultaneously measure the performance of PET system and CT system(Fig. 2).
The structure of PET image performance measurement module is similar to that of NEMA IEC Body phantom, with which $^{18}$F-fluorodeoxyglucose (F-FDG) solution is filled. F-FDG allows the evaluation of glucose metabolism, is the most commonly used tracer in oncology$^{[13]}$. In addition to the 6 hollow spheres specified in the NEMA NU2 standard, 2 hollow spheres with an inner diameter of 4mm and 7mm are added. Among them, 28mm and 37mm spheres are filled with pure water as cold lesions, and the remaining were filled with $^{18}$F solution as hot lesions. The distribution of spheres in phantom is shown in the figure below.

Fig. 2 NIM PET/CT phantom

Fig. 3 The distribution of spheres (Horizontal section of the center of the spheres)
The CT performance measurement module is a round pancake with a diameter of 150mm and a thickness of 20mm. The background is filled with pure water, and is made of non-metallic CT-free artifact material which is equivalent to water. 3 low-contrast CT inserts with same diameter are inserted into with a triangle distribution, whose low contrast resolution is 0.5%, 1.0% and 1.5%.
Image quality control

1）Region of interest（ROI）

ROIs of PET/CT image are placed on PET image and CT image, ROIs of PET image include cold sphere ROIs, hot sphere ROIs, spherical background ROIs and lung insert ROI, and ROIs of CT image include insert internal ROIs and spherical background ROIs.

All sphere ROIs are drawn on the slice centered on the spheres and background ROIs of the same size with concentric distribution are drawn on the background of the at the same level, the concentric groups add up to 12. Besides, the ROIs shall also be drawn on the slices as close as possible to ±1 cm and ±2 cm on either side of the central slice. A total of 60 background ROIs of each size, 12 ROIs on each of five slices shall thus be drawn(Fig. 4). Lung ROI is a circle with diameter of 30±2mm drawn in the center of the simulated lung tube. ROIs of CT image include the internal ROIs of every insert and the three same background ROIs around each insert (Fig. 5).

Fig. 4 Example of background ROIs placement for PET image quality analysis for

(a) NEMA IEC Body phantom and (b) NIM PET/CT phantom.

Twelve 37 mm ROIs are drawn in the background region. Background ROIs for the 10, 13, 17, 22 and 28 mm are drawn concentric to the 37 mm ROIs as indicated in the top background ROI.
Fig. 5 Example of background ROI placement for CT image quality analysis. The solid circles represent the insert ROI and the dotted circles represent the background ROI.

2) Percent contrast

Percent contrast represents the contrast characteristics of hot and cold spheres in a warm background. The image quality assesses the contrast which can be achieved for cold and hot lesions of varying sizes and is intended to provide an indication of lesion detection in clinical whole body study as described in NEMA NU 2 standard[14]. The percent contrast $Q_{H,j}$ for each hot sphere $j$ is defined as:

$$Q_{H,j} = \frac{C_{H,j}}{C_{B,j}} \times 100\%$$

Where $C_{H,j}$ is the average counts in the ROI for sphere $j$ and $C_{B,j}$ is the average of the background ROI counts for sphere $j$, while $a_H$ and $a_B$ is the activity concentration in the hot sphere and the background, respectively.

The percent contrast $Q_{C,j}$ for each cold sphere $j$ is calculated by:

$$Q_{C,j} = \left(1 - \frac{C_{C,j}}{C_{B,j}}\right) \times 100\%$$

Where $C_{C,j}$ and $C_{B,j}$ is the average count of sphere ROI and 60 background ROI for sphere $j$, respectively.

3) Percent background variability
The percent background variability $N_j$ for sphere $j$ is calculated as:

$$N_j = \left( \frac{SD_j}{C_{B,j}} \right) \times 100\%$$  \hspace{1cm} (3)

Where $SD_j$ is the standard deviation of the background ROI counts for sphere $j$.

4) Residual error in lung insert

Relative count error is the percent ratio of the measured averaged count in a cold lung region relative to the mean count in the warm background expressed for measuring the residual error of scatter correction and attenuation correction.

The lung insert in the phantom can be used to measure residual, the relative error $\Delta C_{lung,i}$ in percentage units for each slice $i$ shall be calculated as follows:

$$\Delta C_{lung,i} = \frac{C_{lung,i}}{C_{B,37mm}} \times 100\%$$  \hspace{1cm} (4)

Where $C_{lung,i}$ is the average count in the lung insert ROI in slice $i$, and $C_{B,37mm}$ is the average of the 60 37 mm background ROIs.

5) CT low contrast resolution

Low contrast resolution of CT image is presented by calculating the difference of CT values in and around the CT insert. 10HU difference between CT value means 1.0% of the low contrast resolution and 5HU difference between CT value means 0.5% of the low contrast resolution.

**Data acquisition**

Hot spheres were filled with 4:1 sphere-to-background activity concentration using $^{18}$F-FDG for hot lesion and cold spheres were filled with non-radioactive water for cold lesion when the phantom was scanned(Table 1). Put the phantom on the patient table after effective assembly and started scanning immediately after positioning. Whole-body spiral scan was used for CT image with 512×512 matrix size, 2.0×2.0mm pixel size, 2.00 mm slice thickness and 120.00 kV peak tube voltage. And the PET image acquisition time was about 8 min.
**Table 1** Calculated activity concentrations in background (C_B) and in hot spheres (C_H), total activity (A) at scan start, and time between scanning (Δt) at the PET/CT

|                      | NIM PET/CT phantom | NEMA IEC body phantom |
|----------------------|--------------------|----------------------|
| C_B [kBq/mL]         | 6.6                | 6.8                  | 7.5                  | 6.6                  |
| C_H [kBq/mL]         | 26.4               | 27.2                 | 30.0                 | 26.4                 |
| A [kBq]              | 62900              | 64750                | 71410                | 64750                |
| Δt [min]             | 7                  | 8                    | 8                    | 7                    |

**Image reconstruction**

Scan and reconstruction protocol used in the test was listed in Table 2 and Table 3 respectively, and images were saved as DICOM (Digital Imaging and Communication in Medicine) file format\(^\text{[15]}\), a standard for communication management of medical imaging information and related data.

PET performance parameters, as well as the visibility of lesions in phantoms and patient images, are strongly depend on the applied reconstruction algorithm parameters in general. More complex and accurate models can thus be added to the reconstruction model to better describe the emission and detection processes in PET\(^\text{[11,12]}\). All PET images were reconstructed as 256×256 matrix size, and the voxel size was 2.44mm×3.66mm×2.44mm. The PET data were reconstructed with the baseline ordered-subsets expectation maximization (OSEM) algorithm, and the number of iteration was 2\(^\text{[16,17]}\). The time-of-flight (TOF) reconstruction localizes the decay site based on the arrival time of the photons at the detector, provides adequate temporal resolution and improves image contrast and system sensitivity\(^\text{[18-20]}\), which can also reduce the injection given to patients, thereby reducing the dose of radiation given to the subjects. The point-spared-function (PSF) reconstruction incorporates more information about the detector system response to improve spatial resolution...
and contrast recovery, as well as reduces image distortion\textsuperscript{[11,18,21]}. In order to evaluate
the effect of PSF and TOF on image quality performance, OSEM model, OSEM&PSF
model, OSEM & TOF model and OSEM&PSF&TOF model were applied for evaluation\textsuperscript{[22]}.

### Table 2 PET reconstruction condition

| Phantom                  | Algorithm model | Iteration number | Matrix       | Pixel size  | thickness |
|--------------------------|-----------------|------------------|--------------|-------------|-----------|
| NIM PET/CT phantom       | OSEM            | 2                | 256x256      | 2.44x3.66   | 2.44      |
|                          | OSEM&PSF        |                  |              |             |           |
|                          | OSEM&TOF        |                  |              |             |           |
|                          | OSEM&PSF&TOF    |                  |              |             |           |
| NEMA IEC Body phantom    | OSEM&PSF&TOF    | 2                | 256x256      | 2.44x3.66   | 2.44      |

### Results

**PET image quality parameters**

Image quality assesses the contrast of cold and hot lesions in different sizes to
provide an indicator for the detection of lesion in clinical studies. The lower the
background variability and the higher the contrast indicate that the PET image quality
of PET/CT equipment is better. The lower the residual error is, the higher accuracy of
scattering correction and attenuation correction of PET/CT equipment is.

The NIM PET/CT phantom and NEMA IEC Body phantom were used to measure
the PET image quality performance with same PET/CT equipment and same scan
protocol respectively. The images in Fig. 6 showed similar image quality of NIM
PET/CT phantom and NEMA IEC Body phantom, the cross-section of 37,28,22,17,13
and 10mm could be all observed effectively, which means the measurement results of
the two phantoms were comparable to some extent. Besides, the NIM PET/CT
phantom was designed with 2 smaller spheres (4mm and 7mm), 7mm sphere could be
observed in the 10 o’clock direction of the phantom image, which could evaluate the image quality of smaller areas of PET/CT. The data in Table 4 showed that the NIM PET/CT phantom could measure PET image quality and the accuracy of scatter correction and attenuation correction according to the current standards, and the added spheres had little influence on the contrast, background variability and residual error of the others.

Fig. 6 PET images of a NIM PET/CT phantom and b NEMA IEC Body phantom

Table 3 Comparison of PET image parameters between NIM PET/CT phantom and NEMA IEC Body phantom

| Sphere size [mm] | Contrast [%] | Background variability [%] | Residual error [%] |
|-----------------|--------------|-----------------------------|-------------------|
| NIM PET/CT phantom |
| 37              | 82.11        | 2.05                        |                   |
| 28              | 75.81        | 2.67                        |                   |
| 22              | 73.11        | 3.27                        |                   |
| 17              | 71.43        | 3.86                        |                   |
| 13              | 61.09        | 4.64                        |                   |
| 10              | 45.08        | 5.46                        |                   |
| 7               | 20.52        | 6.45                        |                   |
| 4               | /            | /                           |                   |
Since the device cannot detect the 4mm ball, the measurement data of the 4mm ball in the module measurement result is empty.

In order to evaluate the generalization ability of NIM PET/CT phantom on different PET/CT equipment, 3 PET/CT of different models were used to scan on same scan protocol. The results (Table 5, Fig. 7,8) showed that all equipment could detect 7mm sphere, and the image quality of A and B were similar in areas larger than 10mm. The image quality of equipment C is better than that of equipment A and B, C could further detect the 4mm sphere of the phantom, and the residual error was significantly lower than that of equipment A and B. It could be seen that the NIM PET/CT phantom can realize the image quality measurement of micro-lesion in PET/CT, thus the ability of different equipment to detect micro-lesion could be significantly graded.

**Table 4** Image quality test data of NIM PET/CT on three PET/CT devices

| PET/CT | Sphere size[mm] | Contrast[%] | Background variability[%] | Residual error[%] |
|--------|-----------------|-------------|---------------------------|------------------|
| A      | 37              | 80.27       | 2.78                      | 7.46             |
|   |   |   |
|---|---|---|
| 28 | 74.14 | 3.18 |
| 22 | 78.28 | 3.52 |
| 17 | 74.59 | 3.82 |
| 13 | 63.12 | 4.17 |
| 10 | 39.95 | 4.5  |
|  7 |  5.61 | 4.78 |
|  4 |   /   |   /   |
| 37 | 82.61 | 1.9  |
| 28 | 76.75 | 2.42 |
| 22 | 72.8  | 2.98 |
| 17 | 72.3  | 3.68 |
| 13 | 61.9  | 4.53 |
| 10 | 43.26 | 5.5  |
|  7 | 24.38 | 6.78 |
|  4 |   /   |   /   |
| 37 | 93.26 | 2.09 |
| 28 | 87.21 | 2.69 |
| 22 | 81.12 | 3.05 |
| 17 | 78.54 | 3.76 |
| 13 | 72.08 | 5.01 |
| 10 | 71.27 | 6.49 |
|  7 | 20.06 | 7.3  |
|  4 |  3.22 | 10.01 |

* Neither A nor B can detect the 4mm ball, so the data of the 4mm ball is empty.
CT image quality parameters

The low contrast module of NIM PET/CT phantom contains 3 inserts with low contrast resolution of 1.5%, 1.0% and 0.5% respectively, which can meet the measurement requirements of different levels of PET/CT. Equal-area ROIs were drawn inside and around each insert (Fig. 5), CT values within each ROI were measured, and then the difference of CT values, standard deviation SD and CNR were calculated (Table 5, Fig. 9). The results were in good agreement with the truth-values. The CT values in background ROIs around the same insert were close to the standard deviation data, and the background uniformity was good.

Table 5 CT low contrast resolution detection results

| Low contrast resolution | ROIs     | Insert | Background 1 | Background 2 | Background 3 |
|-------------------------|----------|--------|--------------|--------------|--------------|
|                         | CT value [HU] | 7.73   | 1.04         | 3.30         | 3.32         |
| 0.5%                    | SD       | 2.37   | 2.18         | 2.28         | 1.83         |
|                         | Mean of $\Delta$CT |              |            | 5.18         |              |
|                         | CNR      |        |              | 2.47         |              |
| 1.0%                    | CT value [HU] | 11.16  | 1.61         | 1.57         | 1.04         |
|        | SD  | 2.03 | 2.08 | 1.98 | 2.18 |
|--------|-----|------|------|------|------|
| Mean of $\Delta$CT | 9.75 |
| CNR   | 4.69 |

| CT value [HU] | 20.23 | 4.29 | 4.85 | 5.36 |
| SD           | 1.89  | 2.24 | 1.80 | 2.44 |

1.5%

| Mean of $\Delta$CT | 15.40 |
| CNR                | 7.25  |

* $\Delta$CT=CT_{insert}-CT_{background} i=1,2,3

**Fig. 9** CT values of low contrast insert and background ROI

**Comparison of image reconstruction algorithm models**

In order to compare the image quality of NIM PET/CT phantom under different reconstruction algorithm models, 4 different models of combination of iterative OSEM reconstruction algorithm (OSEM, OSEM&PSF, OSEM&TOF and OSEM&PSF & TOF) were applied to reconstruct PET images with one PET/CT system (Fig. 10), and the PET image quality was improved while using PSF and TOF technology, PSF significantly improved the image resolution and the contrasts of hot spheres. However, when only PSF was used, the edge of the lesions was still vague.
TOF effectively improved edge acutance of lesions, reduced noise, and detected more image details.

In order to quantify the image quality improvement brought by the reconstruction algorithm, the image contrast and background variability were calculated, recorded in table 6 and plotted as a line graph (Fig. 11,12). It can be seen from the line graph that PSF technology can reduce the image noise and enhance the image contrast. However, since PSF technology will reduce the convergence speed of the algorithm\textsuperscript{[22]}, the contrasts of 13-28mm spheres were significantly improved after two iterations, the background variability of the image is also improved by PSF. TOF technology could also improve the image contrast and background variability, greatly improve the overall image quality, and improve the detection limit of the equipment. TOF&PSF technology can significantly reduced noise, enhanced image details, and improved image quality.

\textbf{Fig. 10}—PET images under 4 reconstruction algorithms for a OSEM, b OSEM&PSF, c OSEM&TOF and d OSEM&PSF&TOF
Figure 11 Image quality under 4 reconstruction for a contrast and b for background variability.

Table 6 Image quality parameters under 4 reconstruction models

| Sphere size | Contrast [%] | Background variability [%] |
|-------------|--------------|----------------------------|
|             | OSEM & PSF & TOF | OSEM & TOF | OSEM & PSF | OSEM | OSEM & PSF & TOF | OSEM & TOF | OSEM & PSF | OSEM |
| 37mm        | 87.87        | 88.06        | 75.25       | 75.86       | 2.35 | 3.14 | 3.35 | 3.81 |
| 28mm        | 79.99        | 79.88        | 66.51       | 66.52       | 2.99 | 3.61 | 3.83 | 4.24 |
| 22mm        | 81.16        | 78.31        | 74.8        | 69.14       | 3.53 | 3.99 | 4.48 | 4.82 |
| 17mm        | 79.17        | 69.63        | 69.53       | 62.48       | 4.12 | 4.63 | 5.29 | 5.6  |
| 13mm        | 76.44        | 64.12        | 59.66       | 56.38       | 5.13 | 5.69 | 6.11 | 6.42 |
| 10mm        | 53.81        | 52.27        | 30.3        | 31.41       | 6.03 | 6.89 | 6.89 | 7.33 |
| 7mm         | 5.61         | 4.32         | 7.02        | 8.28        |
| 4mm         |              |              |             |             |

According to the data in Table 6, applying PSF and TOF simultaneously can effectively improve the contrast of details in image and reduce the background variability.

Discussion
This article proposes a performance measurement phantom for PET/CT image quality, which is composed of PET image quality measurement module and CT performance measurement module, can simultaneously detect the quality of PET image and CT image of the PET/CT equipment. Minimal detectability is one of the most important tasks in PET system, which is directly related to the early diagnosis and staging of lesions\(^{23,24}\). In order to improve the sensitivity of medical imageology to diagnosis of early lesions, higher requirements are put forward for the detection ability of medical imaging equipment for small lesions. The minimum inner diameter of the spheres used to measure image quality parameters in the NEMA IEC Body phantom recommended for evaluating PET image quality in existing international standards is 10mm, which cannot detect the measurement limit of PET/CT\(^{[10]}\). At present, a few studies on the detectability of objects with an inner diameter less than 10mm have improved the test level of the detectability limit of PET in NEMA NU2 standard. However, the number of studies is small and there are still some problems. Spheres with inner diameter of 4,5,6,8,12 and 20mm in Esser PET phantom was used to experimentally investigate and compare the detectability of small uptake volumes by Oen et al\(^{[25]}\), Adler et al let a phantom including 7 spheres with inner diameters ranging from 3.95 up to 15.43 mm to be imaged under different conditions for evaluating the detection ability of PET/CT\(^{[10]}\). These phantom studies can be used to detect the limit of small lesions and calculate the image quality parameters. However, sphere diameters designed in these phantoms and in NEMA IEC Body phantom are totally different, thus resulting the impossibly comparison of image quality. So these phantoms does not comply with the NEMA standard and the validity of them can not be exactly verified. In addition, their shapes differ greatly from the human torso and can not better simulate the human body shape. For a better fit with clinical environment, Raymond et al used spheres whose inner diameters are 3,5,9,12 and 15 mm to test the PET system’s ability and limit to detect small lesions or lymph nodes\(^{[26]}\), though the anthropomorphic torso phantom was applied in their study, they still did not solve the problem of effective comparison with NEMA IEC Body phantom. Kadrmas et al used a anthropomorphic torso phantom where 6,8,10,12 and
16 mm silicone spheres for simulating lesions mounted in to evaluate the influence on detection and location performance of lesion under different reconstruction algorithm models of PET\cite{27}, The shell-less design prevents the image quality parameters from being affected by the thickness of spheres, but the radionuclide here is different from the $^{18}$F specified in the NEMA NU2 standard, and the sphere-to-background activity concentration ratio does not meet the NEMA standard, which means the image quality evaluation can not be compared with the NEMA standard yet. Hashimoto et al selected 4.0, 5.0, 6.2, 7.9, 10 and 37 mm spheres in NEMA phantom to investigate the detectability of subcentimeter spheres using a clinical PET/CT scanner\cite{28}, could calculate the image quality parameters while testing the small lesion detection ability of PET. Although there are two spheres with the same sizes as the spheres of NEMA IEC Body, but it is not enough, or the results will be full of noise and not reliable. Therefore, the phantom is still only for evaluating image quality and relative detection limit of PET. To sum up, all the phantoms used in above studies for PET detection limit can not be used for performance measurement of PET equipment. The NIM PET/CT phantom in our study increased 4 mm sphere and 7 mm sphere, met the clinical demand for equipment detection limit, and the combination of the PET performance phantom and CT performance phantom could meet the requirements of PET and CT performance measurements at the same time, greatly reducing the time consuming in PET/CT image quality control.

In order to verify the effectiveness of NIM PET/CT phantom, we imaged the the NEMA IEC Body phantom and our phantom under same scan conditions with one PET/CT. In Fig. 6, 10~28mm spheres are clearly visible with great contrast, and 7mm sphere of the NIM PET/CT phantom is detected. Table 3 presents the image quality and residual error in lung insert of NIM PET/CT phantom is similar to NEMA IEC Body phantom, so NIM PET/CT phantom can not only realize the measurement of image quality, scatter correction accuracy and attenuation correction accuracy, but also the results are comparable with NEMA IEC Body phantom. Besides, it will not
interfere with the conventional image quality measurement recommended in current standards while realizing the image quality detection of micro-lesions.

Then we scan the NIM PET/CT phantom with 3 different PET/CT devices (A, B and C) on same scan protocol, the reconstruction images in Fig. 7 show that 7mm and 4mm spheres are detected on these devices, image quality, scatter correction accuracy and attenuation correction accuracy of C are better than A and B, so the phantom in our study not only can accomplish image quality evaluation of PET/CT small lesion detection, but grade the ability of micro-lesion detection of different equipment obviously.

Based on OSEM iterative algorithm, PSF and TOF were applied to reconstruct PET images (Fig. 10,11). These images shows that PSF technology can significantly improve the contrast of hot lesions, especially for 22mm and 17mm spheres, but it does not obviously improve the contrast of 10mm sphere and can not help detect 7mm and 4mm spheres. Therefore, PSF technology has little effect on improving the micro-lesion detection ability and image quality. In addition, PSF technology can effectively reduce the background variability and improve the image resolution[22]. TOF has been shown to provide faster convergence with comparable signal to noise achieved in fewer iterations, enhance the edge sharpness of details, and improve the image contrast and background variability[16,17], thus improving the image resolution and PET/CT micro-lesion detectability on the basis of not affecting other properties of PET images[20,27,29,30], can be effectively applied in edge detectability. TOF&PSF technology combines the advantages of PSF and TOF technology, can significantly reduce noise and simultaneously enhance image details, or provide wonderful image quality with a lower radiation activity and shorter acquisition time, thus improving patient comfort and reducing radiation stress[22,27], so TOF technology combined with a better algorithm may be a great idea later[20,31], supplemented CT attenuation correction[12] to pursue a detection limit of equipment as far as possible, so as to effectively select clinical PET/CT equipment with more detailed imaging advantages.
The CT values and their standard deviation (SD) data of background ROIs are separately close (Table 7), indicating that the background is of great uniformity. Moreover, due to the good water-equivalent characteristic of the background material, the background is almost integrated with pure water area after injection (Fig. 13). In order to quantify the water-equivalent characteristic of the background, 8 equal-sized circular areas (Fig. 14) were selected to verify the imaging characteristic at the boundary between pure water and the background, and the CT standard deviation value of each circular area was calculated (Table 7). According to the measurement results, the SD is relatively small, that is, the CT value changes smoothly at boundary area and the material water equivalent characteristic of the module are good.

**Fig. 12** The verification of water-equivalent characteristic in background of CT low contrast module for injection of pure water a before and b

**Fig. 13** Noise measurement at the boundary between pure water and background.

The circles 1-8 represent ROI 1-8
Table 7  Results of noise measurement at the boundary between pure water and background

| ROIs | ROI1 | ROI2 | ROI3 | ROI4 | ROI5 | ROI6 | ROI7 | ROI8 |
|------|------|------|------|------|------|------|------|------|
| Standard deviation | 3.31 | 3.36 | 3.57 | 3.65 | 3.26 | 3.43 | 3.29 | 3.32 |
| Average of SD | 3.4 |

For a further understanding of the uniformity of CT performance measurement module, CT values were measured respectively in background, boundary between background and pure water and in pure water area (Fig. 15), recorded the CT value of the ROI in center (ROIc) and in 4 ROIs (ROI1-ROI4) at same circumference of 3 kinds of acquisition pattern modes (Table 8). The CT values of boundary are similar and relatively stable, and the computed CT image uniformity under 3 modes have little difference. Therefore, the CT low-contrast resolution measurement module of NIM PET/CT phantom can also meet the requirements of CT image uniformity measurement.

![Fig. 14 CT value acquisition for image uniformity](image)

- **Fig. 14** CT value acquisition for image uniformity for a background of CT module, b boundary between background and pure water and c pure water area

The circles 1-4 represent ROI 1-4 and the circle c represents ROIc

Table 8 CT image uniformity

| Location       | Background | Boundary | Pure water |
|----------------|------------|----------|------------|
|                |            |          |            |
| ROIs | CT value [HU] | ΔCT value [HU] | CT value [HU] | ΔCT value [HU] | CT value [HU] | ΔCT value [HU] |
|------|---------------|----------------|---------------|----------------|---------------|----------------|
| ROIc | 4.51          | 0              | 4.51          | 0              | 4.51          | 0              |
| ROI1 | 6.1           | 1.59           | 6.21          | 1.7            | 3.74          | 0.77           |
| ROI2 | 5.15          | 0.64           | 5.77          | 1.26           | 2.88          | 1.63           |
| ROI3 | 6.46          | 1.95           | 4.88          | 0.37           | 3.2           | 1.31           |
| ROI4 | 6.58          | 2.07           | 5.78          | 1.27           | 2.66          | 1.85           |
| Image uniformity | 2.07 | 1.7 | 1.85 |

*ΔCT=CT_{ROIi}-CT_{ROIc} \quad i=1,2,3*

**Conclusion**

Based on the existing standard documents, widely used performance measurement phantoms and clinical medical needs, to meet the evaluation requirements of PET image quality and CT image low contrast resolution and overcome the defects of the existing phantoms, our study puts forward the NIM PET/CT phantom, which can cover all test items of NEMA IEC Body phantom and can simultaneously detect the PET image quality and CT image low contrast resolution. The comparability of NIM PET/CT phantom and NEMA IEC Body phantom was proved above.

Performance measurement phantom shall, with the continuous development of medical instruments and clinical testing requirements, escalate optimization. Along with that, the potential uses for PET/CT such as in prognosis and guide therapy are aroused. Higher requests of micro-lesion have been put forward to clinically, the structure of the NEMA IEC Body phantom is also need to be updated at the same time, 2 spheres (4mm and 7mm) were added to the NIM PET/CT phantom for evaluating the PET image quality of micro-lesion and qualitatively evaluating the spatial resolution. Reconstruction parameters optimization is the key to make full use of PSF or TOF, a appropriate reconstruction algorithm can improve the utilization efficiency of phantoms and improve the measurement limit of the equipment.
Additional CT low-contrast resolution measurement module can meet the detection requirements of different grades of PET/CT, such as 1.5%, 1.0% and 0.5%. The detachable design enables each measurement part to be used both alone and in combination, which can not only be used in a variety of measurement environments, but also reduce transportation pressure. Continuous exposure to radionuclides will cause harm to human health, in view of the health and safety of radiologists, fixed lung insert is designed to shorten the duration of drug preparation and reduce the dose of ionizing radiation to radiologists.

Acknowledgements
Not applicable

Authors’ contributions
Sujie Lu evaluated the data, and drafted the manuscript. Peng Zhang created the phantom, assisted in evaluating the data and writing the manuscript. Sujie Lu and Peng Zhang contribute equally. Chengwei Li and Jie Sun assisted in creating the phantom. Wenli Liu and Pu Zhang initiated and designed the study. All authors read and approved the final manuscript.

Funding
We acknowledge support from the National Key Technology R&D Program of China (2016YFF0201004).

Availability of data and materials
The datasets generated during and/or analyzed during the current study are available from the corresponding author on
reasonable request.

**Ethics approval and consent to participate**
Not applicable

**Consent for publication**
Not applicable

**Competing interests**
Not applicable

**Author details**
1. Center for Medical Metrology, National Institute of Metrology, China
Reference

1. Bailey DL, DW T, PE V, MN M. Positron emission tomography[M]. Berlin: 2015.
2. Du J, Li W, Lu K, Xiao B: An overview of multi-modal medical image fusion. Neurocomputing[J] 2016, 215:3.
3. Velasco C, Mota-Cobian A, Mateo J, Espana S: Explicit measurement of multi-tracer arterial input function for PET imaging using blood sampling spectroscopy. EJNMMI Phys[J] 2020, 7(1):7.
4. Rahmim A, Qi J, Sossi V: Resolution modeling in PET imaging: Theory, practice, benefits, and pitfalls. Medical Physics[J] 2013, 40.
5. Farma JM, Santillan AA, Melis M, Walters J, Belinc D, Chen DT, Eikman EA, Malafa M: PET/CT fusion scan enhances CT staging in patients with pancreatic neoplasms. Ann Surg Oncol[J] 2008, 15(9):2465.
6. PET/CT Atlas on Quality Control and Image Artefacts[M]. Vienna:INTERNATIONAL ATOMIC ENERGY AGENCY, 2014.
7. Zhang J, Maniawski P, Knopp MV: Performance evaluation of the next generation solid-state digital photon counting PET/CT system. EJNMMI Research[J] 2018, 8(1).
8. Association NEM. Performance Measurements of Positron Emission Tomographs. Published:NEMA standards publication NU 2–2012, 2012.
9. IEC. Evaluation and routine testing in medical imaging departments - Part 3-5: Acceptance and constancy tests - Imaging performance of computed tomography X-ray equipment. Published, 2019.
10. Adler S, Seidel J, Choyke P, Knopp MV, Binzel K, Zhang J, Barker C, Conant S, Maass-Moreno R: Minimum lesion detectability as a measure of PET system performance. EJNMMI Phys[J] 2017, 4(1):13.
11. Bettinardi V, Presotto L, Rapisarda E, Picchio M, Gianolli L, Gilardi MC: Physical performance of the new hybrid PETCT Discovery-690. Med Phys[J] 2011, 38(10):5394.
12. Ziegler S, Jakoby BW, Braun H, Paulus DH, Quick HH: NEMA image quality phantom measurements and attenuation correction in integrated PET/MR hybrid imaging. EJNMMI Physics[J] 2015, 2(1).
13. Delbeke D: Oncological applications of FDG PET imaging: brain tumors, colorectal cancer lymphoma and melanoma. J Nucl Med[J] 1999, 40:591.
14. Sathiakumar C, Som S, Eberl S, Lin P: NEMA NU 2-2001 performance testing of a Philips Gemini GXL PET/CT scanner. Australasian Physical & Engineering Sciences in Medicine[J] 2010, 33(2):199.
15. ISO 12052:2017 Health informatics — Digital imaging and communication in medicine (DICOM) including workflow and data management. Published, 2017.

16. Taniguchi T, Akamatsu G, Kasahara Y, Mitsumoto K, Baba S, Tsutsui Y, Himuro K, Mikasa S, Kidera D, Sasaki M: Improvement in PET/CT image quality in overweight patients with PSF and TOF. Ann Nucl Med[J] 2015, 29(1):71.

17. Armstrong IS, Kelly MD, Williams HA, Matthews JC: Impact of point spread function modelling and time of flight on FDG uptake measurements in lung lesions using alternative filtering strategies. EJNMMI Physics[J] 2014.

18. Ketabi A, Ghafarian P, Mosleh-Shirazi MA, Mahdavi SR, Ay MR: The influence of using different reconstruction algorithms on sensitivity of quantitative 18F-FDG-PET volumetric measures to background activity variation. Iran J Nucl Med[J] 2018, 26(2):87.

19. Vandenberghe S, van Elmbt L, Guercha M, Clementel E, Verhaeghe J, Bol A, Lemahieu I, Lonneux M: Optimization of time-of-flight reconstruction on Philips GEMINI TF. Eur J Nucl Med Mol Imaging[J] 2009, 36(12):1994.

20. Conti M, Bendriem B, Casey M, Mu C, Kehren F, Michel C, Panin V. Implementation of time-of-flight on CPS HiRez PET scanner[C]. IEEE Symposium Conference Record Nuclear Science 2004., 2004:2796.

21. Panin VY, Kehren F, Michel C, Casey M: Fully 3-D PET reconstruction with system matrix derived from point source measurements. IEEE Trans Med Imaging[J] 2006, 25(7):907.

22. Akamatsu G, Ishikawa K, Mitsumoto K, Taniguchi T, Ohya N, Baba S, Abe K, Sasaki M: 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[J] 2020, 53(11):1716.

23. Bao Q, Chatziioannou AF: Estimation of the minimum detectable activity of preclinical PET imaging systems with an analytical method. Med Phys[J] 2010, 37(11):6070.

24. Schaefferkoetter J, Casey M, Townsend D, El Fakhri G: Clinical impact of time-of-flight and point response modeling in PET reconstructions: a lesion detection study. Phys Med Biol[J] 2013, 58(5):1465.

25. Oen SK, Aasheim LB, Eikenes L, Karlberg AM: Image quality and detectability in Siemens Biograph PET/MRI and PET/CT systems——a phantom study. EJNMMI Phys[J] 2019, 6(1):16.

26. Raylman R, Kison P, Wahl RL: Capabilities of two- and three-dimensional FDG-PET for detecting small lesions and lymph nodes in the upper torso: a dynamic phantom study. European Journal of Nuclear Medicine[J] 1999.

27. Kadrmas DJ, Casey ME, Conti M, Jakoby BW, Lois C, Townsend DW: Impact of time-of-flight on PET tumor detection. J Nucl Med[J] 2009, 50(8):1315.
28. Hashimoto N, Morita K, Tsutsui Y, Himuro K, Baba S, Sasaki M: Time-of-Flight Information Improved the Detectability of Subcentimeter Spheres Using a Clinical PET/CT Scanner. Journal of Nuclear Medicine Technology[J] 2018, 46(3):268.

29. El Fakhri G, Surti S, Trott CM, Scheuermann J, Karp JS: Improvement in lesion detection with whole-body oncologic time-of-flight PET. J Nucl Med[J] 2011, 52(3):347.

30. Jakoby BW, Bercier Y, Conti M, Casey ME, Bendriem B, Townsend DW: Physical and clinical performance of the mCT time-of-flight PET/CT scanner. Phys Med Biol[J] 2011, 56(8):2375.

31. Kadrmas DJ, Casey ME, Black NF, Hamill JJ, Panin VY, Conti M: Experimental comparison of lesion detectability for four fully-3D PET reconstruction schemes. IEEE Trans Med Imaging[J] 2009, 28(4):523.

32. Escott EJ: Role of positron emission tomography/computed tomography (PET/CT) in head and neck cancer. Radiol Clin North Am[J] 2013, 51(5):881.