Phantom design for quality control of Positron Emission Tomography/Computed Tomography (PET/CT) imaging

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Abstract. This research was aimed to develop an in-house phantom for quality control (QC) of image quality in PET/CT imaging. Wax and rice powder were mixed to produce tissue-equivalent materials characterized by Hounsfield Unit (HU). The in-house phantom was two circular cylinders with 20 cm in diameter and 10 cm in length which consists of six symmetric vessel pairs with varied diameters of 4.20, 6.20, 8.30, 9.80, 16.30, and 19.00 mm. Each measurement was performed using radioactivity concentrations of $^{18}$F-FDG with variation from 1 to 17 µCi/mL. Images were displayed with the pixel size of 4×4 mm$^2$. Image quality was evaluated in terms of conversion factor between full-width-half-maximum (FWHM) and actual diameter, and a pixel value for local uniformity of each object. Two types of phantoms have been designed which were liver-equivalent material (LEM) and muscle-equivalent material (MEM). HU and electron densities were (74.17±1.48) HU and 3.396×10$^{23}$ electron/m$^3$ for LEM, while (20.27±0.33) HU and 3.461×10$^{23}$ electron/m$^3$ for MEM, respectively. The conversion factor was initially high at 2.240±0.07 for diameter 4.20 mm, falls to 0.99±0.003 for diameter 9.80 mm, slowly decrease up to 0.82±0.01 at diameter 16.30 mm, and then nearly constant at 0.82 with increasing diameter for both phantoms. The in-house phantom could be used to analyse the image quality performance of PET imaging with a tissue-specific material. The phantom design including the development of tissue-surrogate materials, size, and geometrical considerations of the features will be beneficial for innovating QC tools.

1. Introduction

Positron emission tomography/computed tomography (PET/CT) scanner has been widely used as a molecular imaging tool to achieve a better clinical outcome for both pathological diagnosis and treatment [1]. Integration of PET and CT as a hybrid system generates a reconstructed image with providing physiological information and better anatomic localization. A PET image is clinically quantified based on the radiopharmaceutical distribution in a tissue of a patient, such as a metrics of SUV (standardized uptake value) which corresponds to the metabolic response of cells. Despite the main role of PET image is to determine the functional characterization of tissues, image quality may also affect the qualitative and quantitative assessment of PET images [2], [3].

An evaluation of image quality is a mandatory involved in PET’s quality control (QC) to periodically maintain the performance of a scanner. A phantom is commonly used in conducting QC procedure. However, a trade-off would occur between a phantom study and a clinical condition because of several limitations of a phantom in mimicking a patient scanning. Since the complexity of
uptake variation and a large range of body patient’s geometric affect variation of radioactivity distribution, a phantom study only provides for some indications at limited scanning condition [4]. Since decades, novel phantoms have been proposed to provide a more realistic condition for PET image quantification, as like a utility of 3D-printing technique in representing a detection lesion [5]. However, mostly proposed phantoms have been constructed by acrylic \( (\text{polymethylmethacrylate (PMMA)}) \) or an-organic plastic/polymers. The use of tissue-equivalent material \( (\text{TEM}) \) for phantom provides more surrogate to mimic the radiologic characteristic of human tissues. For these reasons, we developed an in-house tissue-equivalent phantom constructing by our novel organic-based material for image quality’s QC in PET/CT imaging.

2. Material and Method

2.1. Phantom design and construction
An in-house phantom was designed with respect to phantom material, size, and geometric consideration. Material proposed for this phantom was tissue-surrogates. Wax and rice flour were mixed with the mass composition of 70:30 and 60:40 of wax-to-rice flour mass ratios to produce sample materials for liver-equivalent material \( (\text{LEM}) \) and muscle-equivalent material \( (\text{MEM}) \). The mass densities were 1.060 g/cm\(^3\) and 1.050 g/cm\(^3\) for LEM and MEM, respectively [6]. These samples were scanned by CT Scan \( (\text{Siemens Healthineer}) \) at 130 kVp and 100 mAs to characterize Hounsfield Unit \( (\text{HU}) \) and relative electron density \( (\rho_e) \) of samples. Electron density was calculated by a calibration curve of \( \text{HU}-\rho_e \) of CIRS 062M-electron density phantom \( (\text{CIRS, 2013}) \).

The in-house phantom was two-slices of circular cylinders with 20 cm in diameter and 10 cm in length which consist of six symmetric vessel pairs with varied diameters of 4.20, 6.20, 8.30, 9.80, 16.30, and 19.00 mm, as displayed in Figure 1. Detailed object specifications were described in Table 1.

2.2. PET measurement
Measurements were performed by Philips Gemini TOF 16 PET/CT scanner \( (\text{Philips Medical Systems}) \). This PET scanner consists of Lutetium Yttrium Orthosilicate \( (\text{LYSO}) \) crystals with \( 4.0\times4.0\times22 \text{ mm} \) crystal dimension. The coincidence time resolution and coincidence window are of 500 psec and 4.5 nsec, respectively. The axial field of view \( (\text{FOV}) \) extension is 180 mm, while and the

| Table 1. Specification of object detection (vessel pairs) at the novel phantom. |
|-----------------------------------------------|--|--|--|--|
| Object Diameter (mm) \( ^a \) | PMMA-wall thickness (mm) | Object position \( (r, \theta) ^b \) | A region | B region |
|---|---|---|---|
| 1 | 4.2/6.0 | 0.9 | 25 mm, 90° | 25 mm, 270° |
| 2 | 6.2/8.0 | 0.9 | 25 mm, 0° | 25 mm, 180° |
| 3 | 8.3/10.0 | 0.85 | 50 mm, 60° | 50 mm, 240° |
| 4 | 9.8/15.0 | 1.10 | 50 mm, 330° | 50 mm, 150° |
| 5 | 16.3/20.0 | 1.85 | 75 mm, 30° | 75 mm, 210° |
| 6 | 19.0/25.0 | 3.00 | 75 mm, 300° | 75 mm, 120° |

\(^a\)ID is the inner diameter and OD is the outer diameter.  
\(^b\)Each vessel was radially located at the axial-plane of the phantom with a radius from the centre \( r \) in mm & an angle \( \theta \) in degree. Region A and B are defined by region I&IV (\( \theta \) from 180° to 360°) and II&III (\( \theta \) from 0° to 180°) of the circle-quadrant.
trans-axial FOV is 675 mm. Spatial resolutions are 5.9 mm and 5.5 mm for trans-axial and axial, respectively. The system is a hybrid coupled with the 16-slices computed tomography (CT) scanner.

Measurements were conducted by filling a solution of water and $^{18}$F-FDG with radioactivity concentrations varied from 1.89 to 17.12 µCi/mL into each vessel at the phantom. Then, the phantom was scanned by PET/CT scanner with 2.5 minutes of scan duration.

2.3. Imaging Protocol
PET images were reconstructed with CT attenuation correction (CTAC) using BLOB-OS-TF algorithms, then displayed with the pixel size of $4 \times 4 \times 4$ mm$^3$ and matrix of 144 x 144.

2.4. Image analysis
Images were quantified by using ImageJ™ software to extract pixel values. Image quality was evaluated in terms of conversion factor ($CF_{50\%}$) between the object size in a PET image and the actual diameter ($d_{act}$). The conversion factor ($CF_{50\%}$) was calculated by following this equation

$$CF_{50\%} = \frac{FWHM}{d_{act}}$$

with the object size in a PET image represented by full-width-half-maximum (FWHM).
Figure 2. An example image of the phantom (left: PET image, right: PET/CT fusion image) for (a) Liver-equivalent material (LEM), and (b) Muscle-equivalent material (MEM).

3. Results

3.1. Phantom construction

Two types of organic-based materials have been made which were liver-equivalent material (LEM) and muscle-equivalent material (MEM) for the in-house phantom. HU and electron densities were (74.17±1.48) HU and 3.396×10^{23} electron/m$^3$ for LEM, while (20.27±0.33) HU and 3.461×10^{23} electron/m$^3$ for MEM. Confirmed to ICRU [6], differences between electron density from ICRU’s data and our measurement were 3.312% and 0.537% for LEM and MEM, respectively. This study was a preliminary study. The selection of the tissues was firstly because liver is the greatest organ in the abdomen. While muscle is the most tissue in the human body.

3.2. PET image quality evaluation

The reconstructed PET images for LEM and MEM obtained were shown in Figure 2. Each vessel object could be visually observed. By extracting the pixel intensity of each object, the conversion factor (CF_{50\%}) was acquired which was initially high at 2.240±0.07 for diameter 4.20 mm, falls to 0.99±0.003 for diameter 9.80 mm, slowly decrease up to 0.82±0.01 at diameter 16.30 mm, and then nearly constant at 0.82 with increasing diameter for both phantoms, as displayed at Figure 3.

4. Discussion

The novel phantom provided hot lesion uptake with cold-background. Adler et al. (2017) reported that image quality of PET imaging reaches optimum detectability at high radioactivity concentration of lesion-to-background ratio (sphere-to-background ratio, SBR) [7]. The theoretically optimal relative-threshold level (RTL) depends on the sphere size, but not on the SBR. The use of hot lesion object
surrounded by cold-background in the phantom could assess an ‘ideal’ condition of detectability performance of an imaging system, but not represent a clinical condition. In other words, it basically described how a PET imaging performs. Then, it could be beneficial as a part of the quality control of a PET imaging system to evaluate the accuracy of an object size determination. Then, symmetrically located at region A and B on the phantom, six symmetric vessel pairs allowed to evaluate tomographic detectability. Region A and B represent the symmetrical region for the location of vessel objects. To evaluate tomographic detectability as a part of quality control (QC), the difference of CF for symmetric vessel pairs at both regions could assess the symmetric performance of an imaging system for detecting an object, as described on Figure 3(b). Since this is for QC, symmetry is necessary.

The use of material which was tissue-equivalent for phantom could reduce a trade-off or limitation in a phantom study for representing a real scanning. By evaluating CF50% as displayed in Fig.3b, the average CFs obtained from varied radioactivity concentration were similar for both phantom. However, CF at MEM had lower standard deviation than those of LEM. Due to this proposed phantom provided some tissue-surrogate materials, image quality at a specific tissue could be investigated.

In addition, all reconstructed images showed high conversion factor at the small object (4.20 mm). These results confirmed the consequence of partial volume effect (PVE) at small lesion size (4.20 mm). PVE is significantly caused an overestimation of FWHM by spilling out the pixel intensity at the object, particularly for the object size less than three times of the spatial resolution of a scanner. PVE also depends on image acquisition method [8]. In this research, images were reconstructed using pixel size of 4 x 4 mm².

CF50% means correction for an object size at a specific tissue. Particularly when PET image is used for tumor or volume delineation in RT planning, the use of PET image as a guide in pre-treatment for RT treatment planning significantly impacts on the target contouring, such as to extract a biological target volume (BTV). PET image shows gross tumor volume (GTV), clinical target volume (CTV), and planning target volume (PTV) smaller than those of obtained from CT image [9]. Some studies confirmed the use of pixel intensity threshold in determining edge for lesion volume segmentation. Due to the needs of a ‘precise’ object/volume delineating as crucial, these results also proposed the term of CF50% to consider an appropriate threshold value for precise segmentation or object delineation and the quantification of metabolic volume in PET image [10]. Therefore, this novel phantom should be used to confirm a cut-off for pixel intensity threshold or a correction factor of an object size for a specific PET scanner as a part of QC performance.

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**Figure 3.** Conversion factor of FWHM (CF50%) for varied vessel diameters (left) and varied phantom materials (right) including LEM (liver-equivalent material) and MEM (muscle-equivalent material). Vessel-pair objects locate at these phantoms as specification described in Figure 1 and Table 1.
Moreover, there are several advantages when using our phantom for image quality QC. The measurement could use low radioactivity concentration. Consequently, we could increase the radiation protection for the staff who is conducting a QC procedure. Then, the use of hot lesion with cold background could minimize a measurement uncertainty, particularly coming from non-uniform of background concentration and occurring air bubbles. This phantom could provide a quick and easy to use QC tools for evaluating PET IQ. In addition, the phantom construction relatively consumes low cost.

5. Conclusion
The in-house phantom could be used to analyze the image quality performance of PET imaging with the tissue-specific material. The phantom design including the development of tissue-surrogate materials, size, and geometrical considerations of the features will be beneficial for innovating QC tools.

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