Initial tests of a new phantom for investigation of spatial resolution, partial volume effect and detectability in nuclear medicine tomography

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Abstract. A new phantom has been designed that can provide simultaneously different target to background activity ratios with a linearly changing diameter of lesions. The purpose of the study was to describe and perform initial measurements with the phantom aimed to characterize different nuclear medicine tomographic systems and reconstruction algorithms in their performance and behaviour concerning partial volume effect (PVE) and detectability by varying the acquisition parameters and the count statistics. The phantom has an external vessel whose outline is half-cylindrical and allows it to be incorporated into an anthropomorphic thorax phantom. The phantom itself contains 16 fillable cones with an inner diameter linearly decreasing from 16 mm to 2 mm and a wall thickness of 1 mm acrylic glass. They as well as the outer vessel were separately filled with $^{99m}$Tc- and $^{18}$F-solutions respectively of different activity concentrations. The phantom was easy to fill and air bubbles could easily be avoided. Images taken using a SPECT/CT and a PET/CT system are presented as well as evaluations of PVE. The new phantom seems to be useful for comparison and optimisation of different acquisition and reconstruction parameters in nuclear medicine tomographic studies and for comparisons between various tomographic units.

1. Introduction

The majority of phantoms used to characterize a single photon emission computed tomography (SPECT) or positron emission tomography (PET) system are cylinders containing fillable inserts e.g. the Jaszczak PET/SPECT phantom [1] and NEMA IEC body phantom set [2], or phantoms consisting of multiple discrete disks or sheets e.g. the Hoffman phantom [3] and the porous phantom [4]. Tissue-equivalent anthropomorphic phantoms, as the RSD Alderson heart/thorax phantom, are also available [5]. A project named MADEIRA (Minimizing Activity and Dose with Enhanced Image quality by Radiopharmaceutical Administrations) cofunded by the European Commission within the Seventh Euratom Framework Programme aims to optimise the spatial resolution, the signal-to-noise ratio and reduce the radiation dose in 3D nuclear medicine imaging technologies [6]. One way to succeed is to find optimal conditions for different tomographic reconstruction algorithms in terms of number of counts, number of projections and matrix size.

Essentially for detection of lesions in SPECT and PET images is the contrast to noise ratio (CNR) of lesion to background. As there is always an intrinsic resolution volume defined by the camera, collimator, radionuclide, acquisition protocol and reconstruction method, the size of the lesion is also
important. Below a certain volume, the reconstructed intensity tends to diffuse into neighbouring voxels, thereby resulting in very low target to background ratios (underestimation of activity concentration in the target) [7]. This effect is called partial volume effect (PVE) or as proposed by Skretting [8], intensity diffusion. PVE may also involve one further effect if the target is surrounded by background activity, the target signal will have a contamination component coming from the surrounding “spill-in” (overestimation of activity concentration in the target) [9]. To investigate the importance of this effect and to find methods to correct for it, a new patent filed phantom (European patent application no. 09008184, “Phantom for a tomographic medical imaging apparatus”), the “MADEIRA” phantom, has been designed so that it can simultaneously provide different target to background activity ratios with a linearly changing diameter of active or inactive lesions.

The purpose of the present study was to describe and perform initial measurements with this new phantom aimed to characterize different nuclear medicine tomographic systems and reconstruction algorithms in their performance and behaviour concerning PVE and detectability by varying the acquisition parameters and the count statistics.

2. Material and methods

2.1. The MADEIRA phantom
The phantom has an external vessel whose outline is half-cylindrical and allows it to be incorporated into an anthropomorphic thorax phantom [5]. The phantom itself contains 16 cones with an inner diameter linearly decreasing over a length of 19 cm from 16 mm to 2 mm (figure 1). The wall thickness of the cones is 1 mm. The 16 cones are separately fillable with activity in water solution as is the outer vessel. The phantom is constructed of acrylic glass for visual inspection of bubble free filling.

![Figure 1. The construction of the MADEIRA phantom.](image)

2.2. Phantom measurements
The concept was to minimize the number of necessary acquisitions to get a fairly good sampling of all acquisition parameters. At the beginning, we performed one SPECT and one PET measurement, respectively, with very good statistics. Our figures of merit are spatial resolution, PVE and detectability. Spatial resolution was evaluated as the full width at half maximum (FWHM) by drawing profiles across the center of the cones. PVE was evaluated by drawing profiles in the center along the length of the cones. Detectability was studied as a function of CNR and size using region of interests in and outside the cones.

2.2.1. SPECT measurements
The 16 cones were filled with $^{99m}$Tc-solutions of different activity concentrations differing by a factor of $\frac{3}{4}$ from cone to cone; 8 cones above and 8 cones below background activity concentration. The lowest relative activity concentration was 0.1 and the highest 10, where 1 refers to the background activity concentration in the external vessel. The initial activity at the start of acquisition was 530 MBq. Acquisitions were performed with a Symbia T2 SPECT/CT (Siemens Medical Solutions, Forchheim, Germany) in non-circular orbit step and shoot mode. The collimator used was a low energy ultra high resolution (LEUHR) [10]. The applied energy windows were a 15% photo-peak...
window symmetrically placed around 140 keV and a 15% lower scatter window. Each projection was
acquired for 60 s and 240 projections were acquired over 360°. The acquisition matrix was 256×256.
Images were reconstructed using the iterative algorithm ReSPECT 3.0; 8 iterations, nonlinear noise
suppression and no Gaussian filter (Scivis wissenschaftliche Bildverarbeitung GmbH, Göttingen,
Germany).

The number of projections was varied by taking only a subset out of the total projections,
preserving an equidistant sampling of the angle space (120, 80, 60, 48, 40, 30, and 24). The total
number of photons was varied by simulations (increasing Poisson noise), intended to virtually simulate
shorter acquisition time or activity. The matrix size was varied by down sampling the projection
matrix (256, 128, 64). This will make it possible to investigate the influence of count statistics, number
of angles and matrix size simultaneously by just one (real) acquisition. All manipulations were carried
out by using the Scivis scientific visualizer software, producing correct DICOM datasets that can be
reconstructed by any DICOM capable software.

2.2.2. PET measurements
The 16 cones were filled with 18F-solutions of different activity concentrations differing by a factor of
¾ from cone to cone. The lowest relative activity concentration was 0.1 and the highest 10, where 1
refers to the background activity concentration in the external vessel. The initial activity at the start of
acquisition was 145 MBq. Acquisitions were performed with a Gemini 16 PET/CT (Philips
Healthcare, Best, The Netherlands) using matrix size of 144×144 and a scan time of 15 minutes per
bed position. The iterative reconstruction method used was LOR-TF-RAMLA (“BLOB-OS-TF”) with
default settings [11-12].

3. Results
The phantom was easy to fill using a syringe with a long needle and air bubbles could easily be
avoided. The following two subsections will present a selection of the achieved results.

3.1. SPECT measurements
Figure 2 shows representative SPECT images of the MADEIRA phantom. Evaluation of PVE in the
five cones with the highest activity concentration relative to the background activity concentration is
shown in figure 3.

Figure 2. (a) Coronal and (b) axial SPECT images of the MADEIRA phantom
(120 projection angles, matrix size 256, full statistics).
Figure 3. Reconstructed activity concentration normalized to the background activity concentration (measured in a cone-free area inside the vessel) as a function of the diameter of the cone.

Figure 4 shows the reconstructed activity concentration in the constant part as a function of the number of projections used for reconstruction. Figure 5 shows the diameter of the cone, where PVE starts to vary, with the number of projections used for reconstruction.

Figure 4. Reconstructed activity concentration in the constant part as a function of the number of projections used for reconstruction.
3.2. PET measurements

Figure 6 shows representative PET images of the MADEIRA phantom. Evaluation of PVE in the cone with the highest activity concentration relative to the background activity concentration is shown in figure 7.

4. Discussion

There are different available phantoms to characterize a SPECT or PET system [1-5]. The phantoms have various advantages and disadvantages, e.g. cost, levels of contrast and modelling of anatomy. The MADEIRA phantom, used in this study, has been designed so that it can simultaneously provide different target to background activity ratios with a linearly changing diameter of active or inactive lesions. To make measurements with the MADEIRA phantom under realistic clinical conditions, the outer vessel was designed to fit into the RSD Alderson heart/thorax phantom as an alternative to its lung inserts. A special baseplate to the Alderson phantom is under construction and additional measurements will be performed with the MADEIRA phantom in the thorax phantom.
Using the MADEIRA phantom, it is possible to characterize different nuclear medicine tomographic systems and reconstruction algorithms in their performance and behaviour concerning PVE and detectability. Evaluation of PVE for our SPECT measurements was presented in figure 3. As shown in figure 4, the level of reconstructed activity concentration in the constant part was not affected by the number of projections used for reconstruction, but by the diameter of the cone where PVE starts (see figure 5). Consequently, we found that a reduction of the number of projections will increase the importance of PVE.

Figure 6b showed possibilities using the MADEIRA phantom to demonstrate detectability. It is shown that the size of the uptake is reduced with lower activity concentration. Our evaluation of PVE for the PET images did not found any plateau before the starting point of the PVE (see figure 7). This finding was not expected and indicates that the cones should be constructed with larger base diameters. It also shows the shortcomings with the PET system. Normally, we would have expected a better spatial resolution for the PET system compared to the SPECT system. This finding shows the importance of the reconstruction process and it may be due to the chosen noise suppression and regularization mechanisms included in the reconstruction algorithms.

The cone walls were fabricated to be as thin as possible (1 mm) to minimize the “wall effect”. Ideally, the cone walls should have non-zero thickness to prevent the fact that a shell of zero activity separates the cone solution and the background solution. This may affect quantitative measurements and evaluation of lesion detection, but it is believed to be neglected concerning evaluation of PVE.

The phantom used in this study is a prototype and improvements (positioning of cones, larger diameter of cone base, number of cones etc.) will be performed before the phantom will be commercially available in the middle of 2011. The “spill-in” and “spill-out” from other volumes in the cone and from other cones as well as from the background activity will be further studied. It is not possible to disassemble the phantom and this can bring problems with mould due to lack of ventilation. We used pressure air to completely dry the phantom after use. The next generation of the phantom will improve the ease of cleaning (e.g. bigger emptying valves).

5. Conclusion

After minor improvements, the MADEIRA phantom has the potential to be a useful and an important practical tool for comparison and optimisation of different acquisition and reconstruction parameters in nuclear medicine tomographic studies and to find the best working point of a given system as well as for comparisons between various tomographic units.
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