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Image quality phantom and parameters for high spatial resolution small-animal SPECT

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ABSTRACT

At present, generally accepted standards to characterize small-animal single photon emission tomographs (SPECT) do not exist. Whereas for small-animal positron emission tomography (PET), the NEMA NU 4-2008 guidelines are available, such standards are still lacking for small-animal SPECT. More specifically, a dedicated image quality (IQ) phantom and corresponding IQ parameters are absent. The structures of the existing PET IQ phantom are too large to fully characterize the sub-millimeter spatial resolution of modern multi-pinhole SPECT scanners, and its diameter will not fit into all scanners when operating in high spatial resolution mode. We therefore designed and constructed an adapted IQ phantom with smaller internal structures and external diameter, and a facility to guarantee complete filling of the smallest rods. The associated IQ parameters were adapted from NEMA NU 4. An additional parameter, effective whole-body sensitivity, was defined since this was considered relevant in view of the variable size of the field of view and the use of multiple bed positions as encountered in modern small-animal SPECT scanners. The usefulness of the phantom was demonstrated for ^{99m}Tc in a USPECT-II scanner operated in whole-body scanning mode using a multi-pinhole mouse collimator with 0.6 mm pinhole diameter.

1. Introduction

Image quality (IQ) for whole-body, small-animal positron emission tomography (PET) or single photon emission computed tomography (SPECT) can be measured in a phantom that produces images simulating those obtained in a whole-body study of a small rodent with hot lesions, as well as uniform hot and some cold areas. For small-animal PET, a standard phantom with corresponding IQ parameters has been defined by the NEMA NU 4-2008 standards [1]. Fillable rods of different diameters are used to determine the activity recovery coefficients, which are indicative of the spatial resolution. The relative standard deviation in a uniform phantom region is a measure of the signal-to-noise ratio, while the overall uniformity in this region characterizes the attenuation and scatter correction performance. The activity measured in non-radioactive water- and air-filled compartments is indicative of the spill-over and scatter correction performance.

However, generally accepted standards to characterize small-animal SPECT scanners are lacking, and more specifically, a dedicated phantom with exactly defined IQ parameters does not exist. As far as we know, the scientific literature on IQ in small-animal SPECT is limited to qualitative demonstrations of the effective spatial resolution using Derenzo-like phantoms with hot or cold rods [2–8].

The existing NEMA NU 4 PET phantom (NU4IQ phantom), with smallest rod diameter of 1 mm, could be used in multi-pinhole, small-animal SPECT but its structures are too large to fully characterize the sub-millimeter spatial resolution that can be obtained using state-of-the-art scanners. In addition, its outer diameter of 33.5 mm may prevent the NU4IQ phantom to be used in collimators with small transaxial field of view (FOV) as optimal for imaging mice, the most widely used experimental animal. This holds true, e.g., for the USPECT-II mouse collimators in which whole-body scans are limited to 28 mm diameter [7], the GE Triumph X-SPECT when using small radii of rotation (adjustable between 15 and 175 mm), the Siemens Inveon SPECT using mouse collimators with 28 mm transaxial FOV, and the Bioscan NanoSpect using whole-body mouse collimators with 30 mm transaxial FOV (numbers for X-SPECT, Inveon SPECT and NanoSpect are from manufacturer's data sheets).

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The aim of the present work is to design, construct and test an adapted phantom (SPECTIQ phantom) with smaller internal structures and external diameter appropriate for IQ characterization of state-of-the-art high spatial resolution small-animal SPECT scanners. To this end, the NEMA NU 4-2008 IQ parameters have been redefined and extended to match the reduced phantom dimensions and the specific needs in high spatial resolution small-animal SPECT imaging. The use of the SPECTIQ phantom is demonstrated in the USPECT-II scanner for a 0.6 mm diameter multi-pinhole mouse collimator with 69 pinholes using ^{99m}Tc.

2. Methods

The NU4IQ phantom [1] is composed of a main phantom body, which contains a fillable cylindrical chamber with 30 mm diameter and 30 mm length, and a solid part of 20 mm length in which 5 fillable rods have been drilled through with diameters of 1, 2, 3, 4 and 5 mm. It further consists of a lid that attaches to the uniform region of the phantom and supports two cold region chambers. These regions are hollow cylinders of 15 mm length and 8 mm inner diameter with 1 mm wall thickness, and should be filled with non-radioactive water and air.

2.1. SPECTIQ phantom dimensions

Basically, the SPECTIQ phantom is a down-sized version of the NU4IQ phantom with a scaling factor of 0.7 for most of its dimensions. Scaling of the fillable rods, however, was chosen differently. In order to match the high spatial resolution of multi-pinhole SPECT scanners, the rod diameters have been down-sized to 0.35, 0.5, 0.75, 1.0 and 1.5 mm. Their length has been reduced from 20 to 6.5 mm, since micromachining poses limitations on the achievable drilling length of very thin cylindrical holes.

The total volume of the radioactive regions is 6.87 mL. The outer diameter and the length are 23.45 and 40 mm, respectively, leading to a total external phantom volume of 17.3 cm^3. The weight of the filled phantom is 19.2 g, which corresponds to a small mouse.

An overview of the dimensions of all structures of the SPECTIQ phantom is given in Table 1, in which the NU4IQ phantom dimensions have been included for comparison. A schematic drawing and a photograph of the SPECTIQ phantom are presented in Fig. 1. The phantom was constructed by Agile Engineering (Knoxville, TN, USA). According to the manufacturer, the tolerance of the dimensions is 0.005″ (0.127 mm), except for the fillable rods with 0.001″ (0.0254 mm) tolerance. The phantom material is polymethylmethacrylate (density = 1.19 g/cm^3). For practical reasons, an additional hole that can be sealed with a screw plug has been drilled through the removable bottom cover. This hole is positioned in line with the largest, 1.5 mm diameter fillable rod such that a syringe needle can be inserted into this hole and the rod to fill the main phantom compartment. Without this hole, complete filling of the small diameter rods with radioactive solution was not always feasible.

Table 1
Dimensions of the structures of the small-animal SPECT phantom (SPECTIQ) and the NEMA NU 4 image quality phantom (NU4IQ). All measures are in mm, unless otherwise specified.

	SPECTIQ phantom	NU4IQ phantom
Uniform body region		
Outer diameter	23.45	33.5
Inner diameter	21.0	30.0
Inner length	21.0	30.0
Wall thickness	1.225	1.75
Fillable rods		
Diameter 1	0.35	1.0
Diameter 2	0.50	2.0
Diameter 3	0.75	3.0
Diameter 4	1.0	4.0
Diameter 5	1.5	5.0
Length of rods	6.5	20.0
Distance between centers of rods and center of phantom (radius of circle on which rods are positioned)	4.9	7.0
Total radioactive volume (mL)	6.87	20.66
Non-radioactive compartments		
Inner diameter	5.6	8.0
Outer diameter	7.0	10.0
Outer length	10.5	15.0
Inner length	9.8	14.0
Wall thickness	0.7	1.0
Outer phantom dimensions		
Length	40.0	63.0
Diameter	23.45	33.5
External volume (cm^3)	17.3	55.5
Weight of filled phantom (g)	19.2	63.2

2.2. Definition of IQ parameters

The IQ parameters associated with the SPECTIQ phantom are taken from NEMA NU 4 with adaptations to account for the smaller dimensions. These parameters are (i) image noise, expressed as the percentage standard deviation (%STD_{unif}) in a central, cylindrical volume of interest over the center of the uniform region of the phantom, (ii) activity recovery coefficients for the filled rods (RC), expressed as the measured activity concentration in the rods divided by the mean phantom concentration, and (iii) spill-over ratios for the non-radioactive water- and air-filled compartments (SOR_{wat}, SOR_{air}), defined as the activity concentration measured in these compartments divided by the mean phantom concentration.

As for the NU4IQ phantom, the cylindrical region where %STD_{unif} is determined corresponds to 75% of the active diameter and the central two-thirds of the active length, resulting in 15.75 and 7 mm, respectively. RC is determined using the central half of the length of the rods, that is, 3.25 mm. The transverse image pixel coordinates corresponding to the line profiles with maximum averaged activity concentration are determined according to Ref. [1], and RC is calculated as this concentration divided by the mean phantom concentration.

SOR_{wat} and SOR_{air} are calculated in cylindrical regions of half of the physical diameter and the central half of the outer length of the non-radioactive compartments, corresponding to 2.8 and 5.25 mm, respectively.

Standard deviations of RC are determined according to Ref. [1], that is

$$\%STD_{RC} = 100\sqrt{\left(\frac{STD_{\text{line profile}}}{\text{mean}_{\text{line profile}}}\right)^2 + \left(\frac{STD_{\text{unif}}}{\text{mean}_{\text{unif}}}\right)^2}$$

The standard deviations of SOR_{wat} and SOR_{air} are calculated in the same manner.

Although not prescribed by NEMA NU 4, a recovery-coefficient-to-noise ratio, defined as $RCNR_{rod} = 100(RC/\%STD_{RC})$, was determined since it can be a useful parameter to evaluate the trade-off between spatial resolution and activity recovery in small structures versus image noise. This additional parameter was determined for the smallest rod (0.35 mm diameter) for all image reconstruction settings.