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Performance Evaluation for ^{68}Ga and ^{18}F of the ARGUS Small-Animal PET Scanner Based on the NEMA NU-4 Standard

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Abstract— ^{68}Ga is one of the non-conventional nuclides that are being used in preclinical imaging. One disadvantage of ^{68}Ga versus ^{18}F is its larger positron range, which deteriorates the effective spatial resolution and the overall image quality. In this work we present a performance evaluation of the ARGUS small-animal positron emission tomography (PET) scanner for two positron emitters, ^{68}Ga and ^{18}F . These experiments followed the procedure based on the National Electrical Manufacturers Association (NEMA) NU 4-2008 standard. We show how the use of ^{68}Ga may affect the NEMA performance of the system in terms of image quality and spatial resolution. The recovery coefficients (RC) measured in the image-quality phantom ranged from 0.17 to 0.72 for ^{68}Ga and from 0.28 to 0.92 for ^{18}F , using iterative image reconstruction methods and applying all corrections. Under the same conditions the image noise (%STD) in a uniform region was 17.0% for ^{68}Ga and 15.1% for ^{18}F . The respective spillover ratios (SOR) were 0.13 and 0.09 in air, and 0.21 and 0.12 in water. Attenuation correction yielded an improvement of the SOR close to 50% for both radionuclides in the air-filled region. This work evaluates the image reconstruction methods and corrections available in the ARGUS PET for ^{68}Ga and ^{18}F to assess the influence of their physical properties on the NEMA parameters.

peptide agents which have demonstrated a promising application for imaging neuroendocrine tumors [4].

Isotope ^{68}Ga is a generator-produced radionuclide that can be obtained on-site, which may be preferable over a radionuclide produced in a cyclotron (such as ^{18}F). One of the main disadvantages is its high decay energy which yields a large positron range in tissue that may reduce the spatial resolution and increase the blurring of the image due to the partial volume effect. This effect can be corrected by introducing a model of the positron range into the reconstruction software [5], [6]. Furthermore, the knowledge of the point spread function for a long-range positron emitter can be also used to recover the activity in a small lesion [7].

In this work we present a performance evaluation of the ARGUS small-animal PET (SEDECAL, Madrid, Spain) for ^{68}Ga and ^{18}F using the commercial reconstruction and corrections methods available in the scanner. Performance evaluation guidelines for small-animal have been released recently in the NEMA NU-4 2008 standard [8]. We used it to compare the overall performance obtained for both radionuclides. The purpose of this study is to assess the differences in the results on the NEMA parameters but also to evaluate how the physical properties affect it in order to extrapolate the results to other radionuclides.

I. INTRODUCTION

THE most widely used radionuclide in positron emission tomography (PET) is ^{18}F . Nevertheless, other radionuclides such as ^{68}Ga are becoming relevant both in clinical and preclinical applications [1]–[3]. ^{68}Ga can be used to label

II. MATERIALS AND METHODS

A. Scanner and radionuclides

The measurements were carried out in the ARGUS PET/CT hybrid small-animal scanner (aka GE Vista [9]). The PET subsystem is composed of a dual-layer (LYSO and GSO) stationary ring of detector modules. An important feature is its depth-of-interaction (DOI) capability implemented by the dual-layer of crystals in phoswich configuration. The axial field of view (FOV) is 4.8 cm and the effective transaxial FOV is 6.7 cm. In these studies we used FORE+2D-FBP and FORE+2D-OSEM reconstruction algorithms with pixel sizes of 0.38 mm in transverse directions and 0.77 mm in axial direction.

We considered ^{18}F as the reference for the comparison with ^{68}Ga , as ^{18}F is required for most of the measurements by NEMA standards and is the most widely used in PET.

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Table I presents a summary of the physical properties of both radionuclides. ^{68}Ga also emits an additional γ -photon (1.08 MeV) with a low yield (0.03) that produces an insignificant amount of single events.

TABLE I
PHYSICAL PROPERTIES OF ^{18}F AND ^{68}Ga

Property	^{18}F	^{68}Ga
Half-life (min)	109.8	67.6
β^+ yield (%), $E_{\beta^+ \text{ max}}$ (MeV)	97 / 0.63	89 / 1.90
Mean β^+ range in water (mm)	0.6	2.9
Max. β^+ range in water (mm)	2.4	8.2

The production of ^{68}Ga was made on-site from a $^{68}\text{Ge}/^{68}\text{Ga}$ generator (Cyclotron Co. Ltd., Obninsk, Russia). ^{68}Ga was eluted with 6 mL of 0.1 mol/L hydrochloric acid. The ^{68}Ge breakthrough with respect to the eluted ^{68}Ga activity was found to be <0.001%. For ^{18}F measurements, an ^{18}F -FDG agent was purchased from a commercial cyclotron facility.

B. NEMA NU-4 image quality evaluation

The methodology used to assess the image quality follows the recommendations of the NEMA NU 4 standard. This document states the acquisition protocol, the phantom dimensions and the figures of merit to evaluate. The phantom is a polymethylmethacrylate cylinder measuring 50 mm in length and 30 mm in diameter. It consists of three parts: one is composed of five fillable rods used to measure the noise (%STD) and recovery coefficients (RC) as a function of rod diameter; the second is a large uniform region connected to the rods allowing the uniformity to be measured; and the third is composed of two cold region chambers (filled with water and air) that are used to quantify the spillover ratio (SOR).

The recovery coefficients represent the measured activity concentration divided by the actual activity concentration. %STD is the standard deviation divided by mean in the uniform region of the phantom; this parameter is also measured for every rod (%STD_{RC}). The spillover ratio is defined as the activity concentration in cold regions relative to the mean in the uniform region.

A proper comparison between different radionuclides requires an equal number of positron decays, which can be achieved by adjusting either the total scan duration or the initial activity [10]. We chose the option of fixing the initial activity (100 $\mu\text{Ci} \pm 5\%$) and varying the scan duration for the ^{68}Ga acquisition. Therefore, the scan duration was 20 min in the case of ^{18}F , as NEMA recommends, and 20.88 min for ^{68}Ga to collect the same number of coincidences. Data were acquired for a 400-700 keV energy window and reconstructed with all the algorithms available with or without applying scatter and attenuation correction. The attenuation correction is performed using a CT image acquired with the same system.

C. Spatial resolution

For the spatial resolution study, the NEMA NU 4 document advises to use a ^{22}Na point source. In order to compare different nuclides, we filled a glass capillary line source of 0.3 mm diameter and 20 mm length in a water environment. The source was axially centered and moved across the transaxial axis. For these studies, we used a 400-700 keV energy window and the FORE + 2D-FBP reconstruction method.

The slices containing the central 5 mm of the reconstructed images were summed to form a single slice. Profiles in tangential and radial directions were used to report the width as its full width at half-maximum amplitude (FWHM), and the full width at tenth-maximum amplitude (FWTM) for both radionuclides. The fitting method used to assess each FWHM (and FWTM) fulfills the NEMA NU 4 recommendations. We also show the FWHM-to-FWTM ratios to compare the response of both radionuclides and their deviation from a gaussian profile [10], [11].

III. RESULTS

Image-quality recovery coefficients (RC) ranged from 0.17 to 0.72 for ^{68}Ga and from 0.28 to 0.92 for ^{18}F after OSEM reconstruction with 48 image updates and applying all corrections (Fig. 1). Under the same conditions, the image noise (%STD) in the uniform region is 17.0% for ^{68}Ga and 15.1% for ^{18}F .

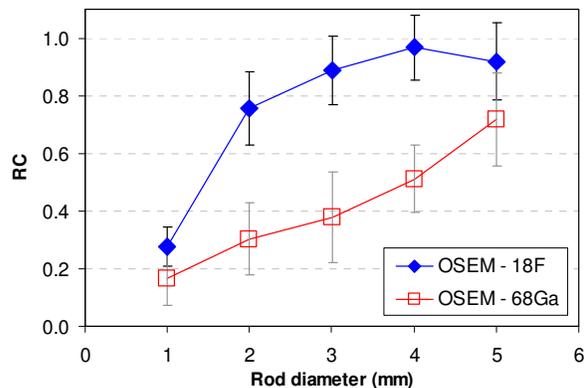


Fig. 1. RC as a function of the rod diameter (1 to 5 mm) for ^{68}Ga and ^{18}F after 2D-OSEM reconstruction. Error bars represent %STD_{RC}.

Using FBP reconstruction the RC values ranged from 0.19 to 0.78 for ^{18}F and from 0.16 to 0.58 for ^{68}Ga (Fig. 2). The level of noise is similar to OSEM reconstruction: %STD in the uniform region is 16.8% for ^{68}Ga and 15.4% for ^{18}F .

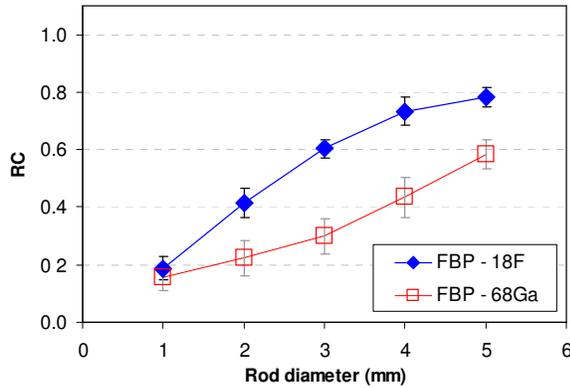


Fig. 2. RC as a function of the rod diameter (1 to 5 mm) for ^{68}Ga and ^{18}F after 2D-FBP reconstruction. Error bars represent $\%STD_{RC}$.

Fig. 3 shows the cross sections of the active rods in the image quality phantom for both radionuclides. The presented images were obtained after FORE + 2D-OSEM reconstruction using all corrections (randoms, scatter and attenuation).

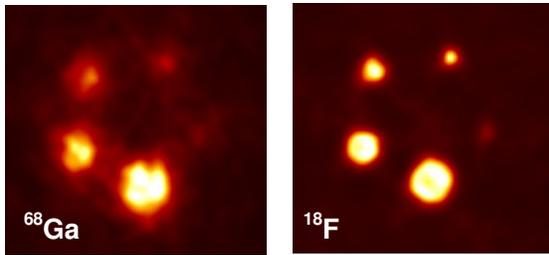


Fig. 3. Transaxial cross section (OSEM reconstruction) of the active rods in the image-quality phantom for ^{68}Ga and ^{18}F . The presented view is obtained by summing the slices containing the central 10 mm of the rods.

The spillover ratios (SOR) were 0.13 and 0.09 in air, and 0.21 and 0.12 in water for ^{68}Ga and ^{18}F respectively. Fig. 4 shows the results for ^{68}Ga after different reconstruction protocols with and without applying attenuation correction. A significant improvement of SOR (reduction $\sim 50\%$) is observed both for FBP and OSEM reconstruction but only in the air-filled region. This result is also obtained with ^{18}F . It is important to remark that SOR in water comprises photon scatter and the effect of positron range (from positrons emitted in the body part of the phantom), whereas only scattered photons contribute to the SOR in air. With long-range positron emitters like ^{68}Ga , a fair comparison of the SOR in water with respect to ^{18}F would require the separation of these two effects. This would be achievable by decreasing the diameter of the region of interest (ROI), however, the dimension of the water-filled compartment in the NEMA NU 4 image quality phantom is too small to fully eliminate positron range effects [10].

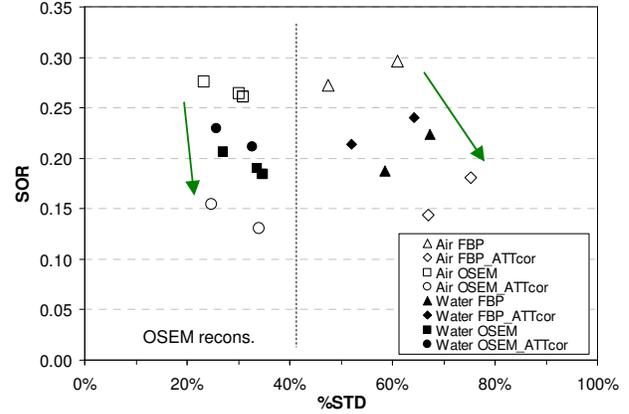


Fig. 4. ^{68}Ga spillover ratios (SOR) and image noise ($\%STD$) in air and water for different reconstructions. The arrows show the improvement of the SOR in the air-filled region after applying attenuation correction ("ATTcor").

With regard to spatial resolution, the averaged FWHM measured over transaxial directions at the centre of the FOV is 2.2 mm (FWTM: 5.8 mm) for ^{68}Ga and 1.6 mm (FWTM: 3.2 mm) for ^{18}F . Fig. 5 shows the FWHM and FWTM obtained for different radial offsets. The important difference in FWTM between both radionuclides is consistent with their different maximum energies of the emitted positrons.

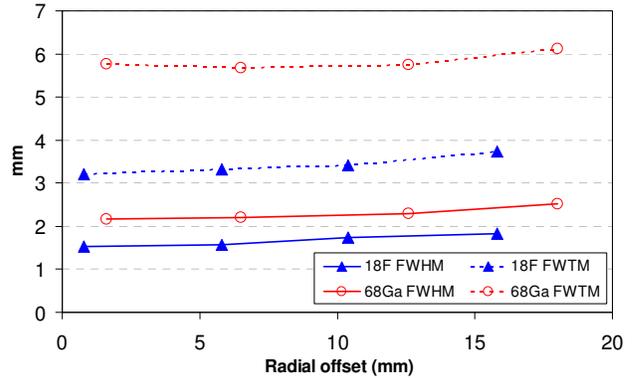


Fig. 5. Transaxial spatial resolution (average tangential and radial directions) measured for the glass capillary at different radial positions. 400-700 keV energy window and FORE + 2D-FBP reconstruction.

The FWHM-to-FWTM ratio is 0.50 for ^{18}F and 0.39 for ^{68}Ga . An important deviation from a gaussian profile (ratio ~ 0.55) is observed for ^{68}Ga . These results are in accordance with those measured in the Siemens Inveon small-animal PET (ratios of 0.51 and 0.38 for ^{18}F and ^{68}Ga , respectively, using a similar measuring method [10]), and the values of spatial resolution modelled in [11] for an imaging scanner with intrinsic resolution of 1.5 mm (in this case, the FWHM-to-FWTM ratio is 0.54 for ^{18}F and 0.39 for ^{68}Ga).

IV. DISCUSSION AND CONCLUSIONS

We have presented a performance comparison between ^{68}Ga and ^{18}F of the ARGUS PET in terms of image quality and spatial resolution. ^{18}F produces better NEMA image quality both for FBP and OSEM reconstruction. The expected improvement after OSEM reconstruction in the RC results, with respect to FBP, is more relevant for ^{18}F than for ^{68}Ga . For these studies the parameters of the OSEM algorithm were selected in order to produce the same level of noise in the uniform region of the phantom than the analytical method (FBP), in such a way that RCs are compared for the same background noise.

Among all corrections available in the system (randoms, scatter and attenuation), attenuation correction yielded the most important improvement (~50%) of the SOR values in the air-filled region. This result was observed for both nuclides.

The studies presented show that NEMA image quality protocols can be adapted for specific characterizations of small-animal systems with long-range positron emitters, such as ^{68}Ga . Furthermore, performance evaluations using different isotopes must be taken into account for an accurate quantitative PET imaging.

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